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The Risk of Ending a Solar Radiation Management Program Abruptly

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The Risk of Ending a Solar Radiation Management Program Abruptly

by

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Dedication

I dedicate this report to my parents (Mrs. Suman Agrawal and Mr. Manmohan Agrawal) for their love, support and belief in me.

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Abstract

The Risk of Ending a Solar Radiation Management Program Abruptly

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Climate change as a result of anthropogenic activities calls for reduction of greenhouse gas emissions to avoid dangerous consequences on society. However, abatement of emission is a costly process and adversely affects the economic growth. Recent proposals, therefore, suggested a different approach i.e. Geoengineering. Instead of controlling emissions, Geoengineering modifies the climate by changing global energy fluxes either by increasing the amount of outgoing infrared radiation through reduction of greenhouse gases (GHGs) or by decreasing the amount of solar radiation falling upon the earth's surface by increasing the albedo (reflectivity) of the atmosphere. Most popular geoengineering strategies are Air Capture (AC) and Solar Radiation Management (SRM) and many economic studies have shown large net monetary benefits with their application. But, these studies neglected the risks which can arise due to potential failure to sustain SRM after few decade of its deployment. There is a concern that application of SRM will lead to increase in concentration of carbon-dioxide in atmosphere and its abrupt turning off can lead to rise in temperature and thereby huge monetary losses. In this report, consequences of abruptly turning off of SRM have been analyzed. A modified version of DICE (Dynamic Integrated model of Climate and the Economy) model that incorporates negative SRM forcing and a two phase optimization procedure has been used for the study. Different outcomes such as net change in NPV of climate damage and abatement costs, maximum mean temperature of earth surface, increase in temperature, emissions control rate, carbon taxes, etc due to abrupt ending of SRM have been analyzed. Results show that application of SRM with a risk of abrupt turnoff is still more profitable compared to not using it at all.

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CHAPTER 1

1.0 INTRODUCTION

Environmental changes driven by anthropogenic sources are posing natural hazards by altering the flow of natural services throughout the world. Climate change as a result of these activities calls for reduction of green house gas emissions to avoid dangerous consequences on society. However, recent proposals suggested a different approach to geoengineer the climate using techniques like Air Capture (AC) and Solar Radiation Management (SRM). Economic studies (Nordhaus 2008, Bickel and Lane 2009) show that using SRM in place of carbon-dioxide emission abatement (which is hard to implement due to reluctance of many nations as it hinders economic progress) is a viable and may be a more profitable approach.

However, these studies assumed that once applied geoengineering will be continued forever and thereby did not account for the risks which can arise due to potential failure to sustain it after few decades of deployment. Geoengineering controls climate change by changing the global solar fluxes and as such its abrupt turning off may trigger large damages. In this report, consequences of abruptly turning off of SRM have been studied. Results show that application of SRM even for a short unknown duration is more profitable compared to not using it at all.

1.1 CLIMATE CHANGE AND BENEFIT-COST ANALYSIS

Global average surface temperature rose by a central estimate of 0.6°C from 1861 to 2000, up by 0.15°C from the corresponding SAR estimate through 1994. The most likely reason for this increase in temperature over the last 50 years is an increase in greenhouse gas concentrations, primarily carbon dioxide (IPCC 2007). The atmospheric carbon dioxide concentration has increased from 280 parts per million at the beginning of industrial revolution to 384 ppm in 2007 (Moore 2008). The other contributors to the rise in mean temperature include water vapor, methane, nitrous oxide, chlorofluorocarbons but they are present in very small amount. These Green House Gases (GHGs) in Earth's atmosphere cause the planet's surface to be about 30°C warmer than would otherwise and thereby play a critical role in sustaining life.

Altering of ecosystem due to anthropogenic activities like burning of fossil fuels, deforestation, agriculture and husbandry add GHG stocks in the Earth's atmosphere (IPCC, 2007) increasing its concentration. These gases absorb heat radiation and radiate a fraction of it back to earth's surface. Thus, higher GHG concentrations will raise global mean temperature (IPCC, 2007) and can cause three distinct kinds of problems depending upon likelihood of their occurrence, their probable timing, and incidence of their costs and benefits (Bickel and Lane, 2009).

1.1.1 Gradual Climate Change

Due to continuous increase in GHGs concentrations, gradual warming is likely to occur over long periods of time. Benefits of gradual warming include higher crop yields from longer growing seasons, lesser mortality from cold, decrease in heating costs etc (Bickel and Lane, 2009). Costs (or disadvantages) include fall in yield of some crops, increase in sea level, increase in intensity of storms, increase in health problems and cooling costs due to increased heat waves, and possible increase in spread of tropical diseases. Over the time, the costs will dominate the benefits. Nonetheless, in midst of all these changes, societies will adapt and industrial sector is much likely to be unaffected. Thus the pace of economic growth is expected to compensate for the cost if the climate changes gradually.

1.1.2 Rapid Climate Change

Rapid climate change will induce large costs due to the increase in cost of adaptation. The probability of such a change is low however, the risks cannot be ruled out (Bickel and Lane, 2009). One current worry is that increase in mean temperature may trigger large-scale methane release from the Arctic and sub-Arctic tundra which in turn may induce a self-reinforcing process as methane itself is a greenhouse gas. Snow cover has 'very likely' declined by about 10 percent since the late 1960s. This warming might accelerate the melting of polar icecaps which can lead to rapid rise in sea level doing serious damage to coastal cities, shift in pattern of ocean currents, change in distribution of temperatures and precipitation etc. The costs of adapting to these changes will be very high.

1.1.3 Ocean Acidification

Oceans act as sinks and absorb a considerable amount of carbon-dioxide from the atmosphere. In this process, the acidity of ocean increases (Royal Society, 2005) which can disrupt the marine ecosystem. This can cause some economic damage and is causing concern among some scientists.

Due to significant potential of damage, global warming has attracted a lot of attention in past few years. Reduction in concentration of GHGs can alleviate global warming but the measures to reduce the intensity of the GHGs emissions would act slowly on the climate system due to the sizeable inertia of the carbon cycle and require sizeable investments (Barker et al. 2007, Nordhaus 2008). This demands deployment of technology that can curtail the harmful effects of global warming at a reasonable cost and in a timely fashion

1.2 CLIMATE ENGINEERING

Climate Engineering (often referred to as Geoengineering) which is described by US environmental protection agency as “the intentional modification of Earth’s environment to promote habitability” (EPA, 2009) is the most widely discussed current concepts of modifying climate to alleviate the harmful effects of global warming. It is being explored by reputed institutions like National Academy of Sciences in the US, The Royal Society of Britain, American Metrological Society etc. Prominent scientists and economists such as Edward Teller, Paul Crutzen, Ralph Cicerone, Scott Barrett, William Nordhaus, Thomas Schelling etc have stressed on the need for further study (Lane and Montgomery, 2008; Barrett, 2007a; Summers, 2007). This appears to be a promising area of research and will be discussed in detail in Chapter 2.

1.3 ORGANIZATION OF THE REPORT

This chapter provides an understanding of the causes and consequences of global warming and the need to find a solution to avoid huge damages in future. This chapter also introduced the concept of “Climate Engineering” which is being viewed as potential solution to the problem at hand. Rest of the report is organized as follows: Chapter 2 discusses about various Geoengineering strategies, their advantages and disadvantages. It also provides a brief overview of existing literature regarding cost-benefit analysis of Geoengineering strategies. Chapter 3 discusses the Dynamic Integrated Model of Climate and Economy (DICE) and the modifications made to study the effect of unplanned turning off of SRM. Results obtained from the analysis are described in Chapter 4 along with detailed comparisons against benefits of using SRM for a long time (forever) and not using any kind of radiative forcing at all. Finally, Chapter 5 concludes the report.

CHAPTER 2

2.0 LITERATURE REVIEW

Climate Engineering (CE) is a deliberate modification of the climate in an effort to offset climate change. It alters the global energy fluxes either by increasing the amount of outgoing infrared radiation through reduction of greenhouse gases (GHGs) or by decreasing the amount of solar radiation falling upon the earth's surface by increasing the albedo (reflectivity) of the atmosphere (Keith and Dowlatabadi, 1992). Different techniques of climate engineering like Solar Radiation Management, Air Capture, Arctic Geoengineering, Heat Transport etc are currently being studied to identify the advantages and risks associated with their deployment. Out of these, solar radiation management (SRM) and air capture (AC) seems most promising (Bickel and Lane, 2009) and are classified as (Figure 2.1):

i) Increasing reflectivity of short-wave radiation within the atmosphere or at the surface (SRM) thereby reducing short wave radiation

ii) Reduction in the amount of long-wave solar radiation reaching the earth's atmosphere through the removal of CO_2 from the atmosphere (AC)

2.1 SOLAR RADIATION MANAGEMENT

SRM aims at offsetting the warming caused by the build-up of man-made GHGs in the atmosphere by reducing the amount of solar energy absorbed by the Earth. Greenhouse gases in the atmosphere absorb long-wave radiation (thermal infrared or heat) and then radiate it in all directions including a fraction back to Earth's surface. This leads to an imbalance in energy and rise in Earth's temperature. SRM does not directly try to reduce the concentration of GHGs from the atmosphere to avoid global warming rather it reflects back into space a small part of Sun's incoming short-wave radiation. This results in lower overall temperature of earth's surface even with high level of GHGs thereby counteracting some risks of global warming (Lenton and Vaughan 2009). Reflecting only one or two percent of sunlight that strikes the earth's surface will cool the planet by an amount roughly equal to the warming that is likely from doubling the pre-industrial levels of greenhouse gases (Lenton and Vaughan 2009).

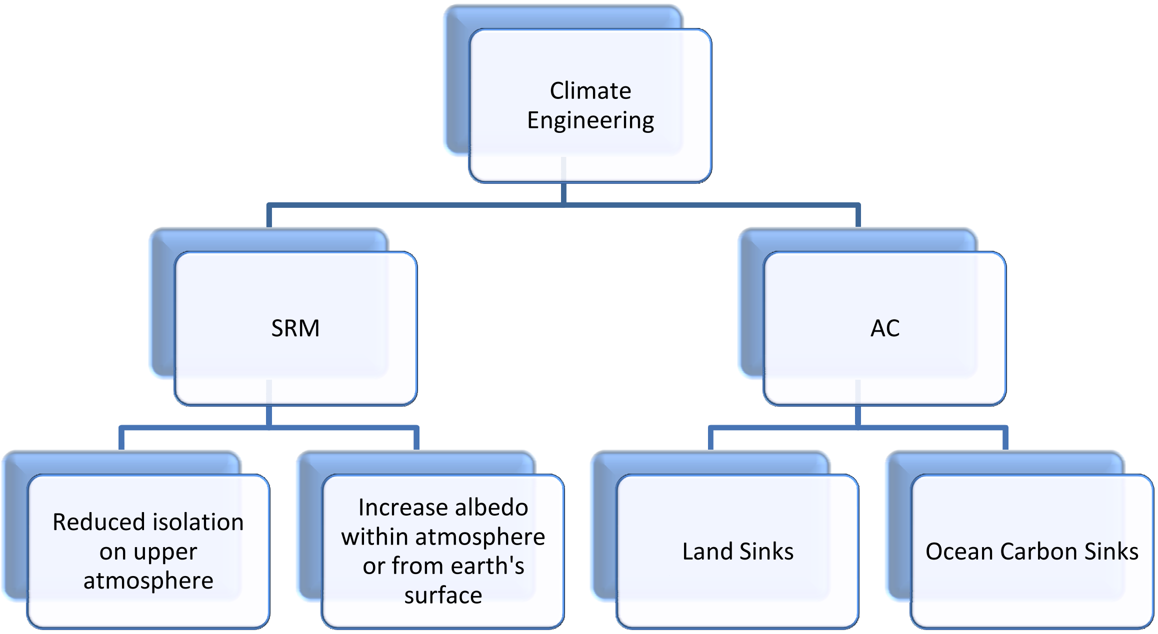

Figure 2.1 Classification of Geoengineering Techniques

SRM options currently available differ in scale and range of their possible use. In addition, there is a possibility that many of these options might have adverse effect on Earth's ecosystems. Surface level approaches can prove locally useful but they cannot offer a global level solution. This report will only detail major concepts that might be able to offset the warming on global scale.

2.1.1 Marine Cloud Whitening

This involves producing an extremely fine mist of sea water droplets which would be lofted upwards and would form a moist sea salt aerosol. These particles will act as site for cloud droplets to form once they rise to the marine cloud layer. These up-lofted droplets would add to the effects of natural sea salt and other small particles, which are collectively called cloud condensation nuclei (Latham et al. 2008). This will increase the cloud albedo to reflect solar energy back to outer space (Salter et al. 2008).

Various schemes have been suggested to bring this plan to action of which spraying seawater in the atmosphere to increase the reflectiveness of clouds and ocean sulfur cycle enhancement are prominent. The extra condensation nuclei created by the spray will change the size distribution of the drops in existing clouds to make them whiter. The sprayers would use a fleet of around 1500 unmanned rotor ships known as *Flettner* vessels to spray mist created from seawater into the air to thicken clouds and thus reflect more radiation from the Earth. The whitening is achieved as a result of the Twomey Effect. Preliminary calculations suggest that the marine clouds of the type considered by this approach contribute to cooling, and that augmenting this effect could, in theory, produce enough cooling to offset a doubling of atmospheric GHG concentrations. Ocean sulfur cycle enhancement involves enhancing the natural sulfur cycle in the Southern Ocean by fertilizing a small portion with iron in order to enhance dimethyl sulfide production and cloud reflectivity (Wingenter et al. 2007). The goal is to slow Antarctic ice from melting and raising sea level. This technique can give only 0.016 W/m^2 of global forcing but as it is a regionally acting technique with effects concentrated into Antarctica it will help to maintain its climate.

2.1.2 Stratospheric Aerosols

This concept of SRM involves inserting aerosols into the stratosphere and is probably most discussed than any other concepts. This SRM strategy is projected to act faster and be considerably cheaper when compared to CO2 abatement (Nordhaus 2001, Wigley 2006). Aerosol can influence radiative influxes either by optical scattering and re-radiation, or indirectly by increasing the albedo and lifetime of clouds. Balloons or artillery guns are currently being discussed as potential carriers to transport sulfur to the outer atmosphere. Budyko (1982) calculated that injection of about 107 tons per annum into the stratosphere would roughly counter the effect of doubled CO2 on the global radiative balance.

Volcanic eruptions of Tambora, Krakatau, El Chicon and Pinatubo inserted loft particles in the earth’s atmosphere enhancing its brightness which in turn reflected a portion of sunlight that would have warmed the surface. The cooling from the large Pinatubo eruption that occurred in 1991 was especially well-documented (Robock and Mao, 1995). However, the emulation of cooling caused by tropical eruptions wouldn’t be easy and require injection of submicron sized particles into the stratosphere. Particles will scatter the light back to space and as more and more sunlight gets reflected back into space, earth will cool.

Sulfur-dioxide is widely discussed candidate for the material to be injected. Other candidates include hydrogen sulfide and soot (Crutzen, 2006). In fact a broad range of particles can be injected and its even possible to develop engineered particles that might improve reflective properties and residence times (Teller et al. 2003). Engineered particles, in comparison with sulfates or similar materials, would raise material cost per unit of weight, but the total mass needed would be considerably smaller to deflect the desired quantity of sunlight.

Delivery mechanism to inject these particles depends on the intended purpose of the SRM program (NAS 1992). For example, SRM can be deployed to cool the Arctic in response to threat of methane release or it could serve as a large scale experiment moving toward a larger scale deployment. For Arctic deployment, large cargo planes or aerial tanker can be used but for global deployment, fighter aircrafts or planes resembling them seem plausible candidates as the injection needs to be done at higher altitudes. Another option involve combining both aerial tanker and fighter aircrafts and some thought has also been given to balloons (Robock et al. 2009).

2.1.3 Space Sunshade

Early (1989) proposed the idea of using space sunshades to block the long-wave radiation entering the earth’s atmosphere. A new version of the concept is proposed by Angel (2006) for implementing actual scattering of incoming sunlight by the placement of space-based sunshade at the Lagrange point (L1) between the earth and the Sun. The scheme is designed to reduce 1.8% of the solar insolation entering the Earth. The sunlight reflected off would be enough to hinder the global warming and help us give ample time to cut our emissions back on earth.

This concept is immensely complex and intricate and would include large scale development and ground operations, as well as the flyer production and transportation. It requires huge investments which are several orders of magnitude than other discussed SRM strategies. Albeit its large fixed cost, this project offers several advantages like lifetime of many decades, low operating costs, and ability to halt the cooling at any point of time if required just by reorienting the shield. In addition, this would not change the composition of atmosphere and ocean beyond their loading with greenhouse gases (Lane et al. 2007). The disadvantages of the approach include enormous area and mass required, high technical requirements, issues related to material, launch costs, propulsion and station keeping thereby making the concept less appealing compared to alternative SRM strategies. Figure 2.2 shows design of space sunshades.

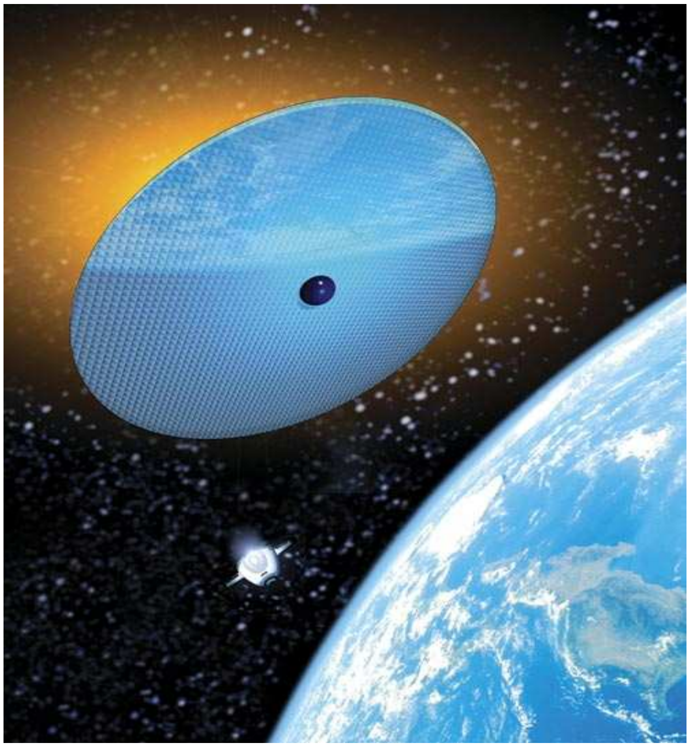

Figure 2.2 Design of a space sunshade

2.1.4 Paint White

Application of white paint to the roofs of houses and cars in hot areas would allow heat to get reflected and painting roofs black where it is cold will reduce the need for heating.

Local modification of surface albedo accomplished by whitening of urban areas can play an important role in reducing the effects of surface warming. This is an excellent approach which can decrease the consumption of energy in households thereby reducing the amount of carbon dioxide emissions. In addition to being cheap and viable, it won't affect the environment or endanger it. But the scoxpe of this strategy is only local and it can cool a region or a city and reduce the smog intensity. The energy and air-quality savings resulting from increasing urban surface albedo in the U.S. alone can exceed $2 billion per year. Table 2.1 summarizes different SRM strategies.

2.2 AIR CAPTURE

Air capture is another group of popular SRM concept which works on a different principle. It recommends capturing of atmospheric CO_2 and securing it in land of sea based sinks. Thus, unlike SRM which attack on shortwave radiations, AC attacks on the impact of GHG concentrations by attacking on long wave radiations. Pielke Jr. (2009) describes a number of possible air capture technologies. Photosynthesis is natural approach to capture carbon and therefore biomass could fuel power plants operation with carbon capture and storage systems. Other similar concept suggests fertilization of oceans to increase carbon storage in deep ocean sinks (Lenton and Vaughan 2009). AC offers advantages some over GHG controls and can circumvent many of the problems that are plaguing GHG controls. In spite of its high implementation cost, AC is building up a base of scientific knowledge as CO_2 capture is clearly possible and some of the well known existing processes exist for doing it.

2.3 COST BENEFIT ANALYSIS OF GEOENGINEERING

Geoengineering entails three different types of cost: direct, indirect and transaction cost. Direct cost refers to the amount spend in developing and deploying the technology, indirect cost reflects the cost due to harmful effects as a result of using these technologies (Barrett, 2007b), while transaction cost includes the routine cost of monitoring and measuring the performance as well as the cost of resources consumed in bargaining to secure agreement to use Geoengineering. Therefore, deployment of Geoengineering strategies can only be justified if the benefits of using them outweigh the costs.

Table 2.1 Summary of Different SRM strategies

SRM Strategy	Cost ($)	Benefits	Risks
Cloud Seeders	Several Billion	Relatively simple and benign as it is based on natural processes of 'ocean spray'	Affect hydrological cycle, Contaminate shorelines, Damage Fisheries
Stratospheric Aerosols	$50 billion	Simple, relatively cheaper than other strategies, easy to implement	Causes acid rain, Affects the crop production, Shift in hydrological cycle, Cause abrupt weather changes, Respiratory diseases, Activate atmospheric reactions with Chlorine and CFC's
Space Sunshade	> $5 Trillion	Clean, high life of sunshades after deployment, can be used to produce solar energy	Does not address ocean acidification problems, Failure of sunshade can increase the temperature drastically, Affects the hydrological cycle
Paint White	$1.1 Trillion	Clean, no adverse effect on environment, easy to deploy	Might not be able to completely alleviate the effects of global warning as it's a local approach

Nordhaus (2008) proposed a Dynamic Integrated model of Climate and Economy (DICE) to compare alternative options dealing with climate change. Their model converts all the economic activities into a common unit of account and then weighs different approaches by their corresponding impacts on the total amount. DICE combines equations from economics, ecology, and earth sciences and run them using mathematical optimization software to predict economic and environmental outcomes. Initial run of the model without any policy restrictions indicated a rapid continued increase in CO_2 emissions from 7.4 billion tons of carbon per year in 2005 to 19 billion tons per year in 2100. It also predicted a mean global surface temperature increase by 3.1^{o}C in 2100 relative to 1900. The climate changes associated with this rise in temperature are estimated to produce damages by almost 3 percent of global output in 2100. Nordhaus (2008) also analyzed a wide range of alternative policy (centered towards GHG abatement) responses to global warming. Their analysis indicated that even after optimal policy has been taken, there will still be substantial residual damages from climate change (17 trillion dollars). The climate damages are not eliminated as additional cost of abatement would be more than additional reduction in damages.

Carlin (2007), Crutzen (2006), Teller et al. (2003), Wigley (2006) proposed Geoengineering strategies to potentially reduce inertia and cost problems of greenhouse gas abatement strategies. Wigley (2006) showed that geoengineering strategies are faster and cheaper to implement compared to CO_2 abatement. Bickel and Lane (2009) analyzed the effects of Solar Radiation Management and Air Capture on global warming. For the analysis, authors modified forcing equation in DICE model and incorporated forcing due to SRM/AC. Their results estimated a direct benefit-cost ratio of around 25 to 1 for aerosols and around 5000 to 1 for cloud albedo enhancement. However, their analysis assumed that after deployment, SRM/AC forcing will be maintained for a long period of time. Theeyattuparampil[1] (2008) performed a benefit-cost analysis for the case where SRM and AC are applied for short periods of time. Their results showed that application of SRM and AC even for short time frames is better compared to not using it at all and results in net decrease in damages. However, in their model, authors fixed the time periods for which SRM and AC are applied. The optimization model knew in advance that SRM will be turned off after a certain given interval of time and performed global optimization taking into account this information. Thus, it is quite different from abrupt turning off of SRM where the actual time at which SRM is turned off is not known in

[1] Under the supervision of Dr. J. Eric Bickel

advance. In fact, none of the approaches (to the best of author's knowledge) studied the effects of abrupt or unplanned turning off of SRM which can occur due to various reasons like war, economic crisis, disagreement between countries using geoengineering, lack of interest to continue SRM, etc. This report is motivated by this interesting research gap and tries to answer questions like: Is it worth using SRM with a probability of abrupt turnoff? How the damages caused due to abrupt turning off of SRM compared to not using geoengineering at all? What are the other effects it will cause? How will it affect the global mean temperature, emission control rate and carbon costs? Next section describes the mathematical model using which all these questions have been answered.

CHAPTER 3

3.0 DYNAMIC INTEGRATED MODEL OF CLIMATE AND ECONOMY

In this report, DICE model has been used to study to study the effects of applying SRM on climate change and economic growth. DICE is an economic optimal growth model which combines global carbon cycle, the climate system, and the economic impacts of climate change. It relates economic growth with CO_2 emissions, CO_2 emissions with temperature change, and temperature change to climate damage. The model is briefly described below (a more detailed description of the model can be found in Nordhaus (2008)).

3.1 THE ECONOMIC MODEL

The Dice model is aimed at maximizing the generalized level of consumption now and in the future. For this purpose, mathematically, the objective of DICE model is to maximize a social welfare function that is the discounted sum of utility of per capita consumption. This social welfare function is represented as a relationship between three basic value judgments:

- Higher levels of consumption have higher worth.
- Marginal value of consumption decreases with increase in consumption
- Society will undertake investments to increase consumption in periods where marginal utility of consumption is highest.

Thus, the objective function is discounted sum of utility of consumption U[c(t), L(t)] given as:

$$\max_{\{c(t)\}} \sum_t U[c(t), L(t)]R(t), \qquad (3.1)$$

here, U is the flow of utility, c(t) is the per capita consumption at time t, L(t) represents the population (labor input) at time t, and R(t) is the discount factor which is a function of pure rate of social time preference (ρ):

$$R(t) = (1+\rho)^{-t}. \tag{3.2}$$

ρ is the only parameter in this equation and its value is taken as 1.5% per year. The model operates in time steps of 10 years. Another convention model follows is that stocks are measured at the beginning of each period. The utility function is defined as an isoelastic function of marginal utility of consumption, α:

$$U[c(t), L(t)] = L(t)\{[c(t)]^{1-\alpha} - 1\}/(1-\alpha). \tag{3.3}$$

The marginal value of consumption of 2 calibrates the utility function to match market returns and has been used in this work.

Total output Q(t) is assumed to be constant-returns to scale Cobb-Douglas production functions of capitol K(t), labor L(t), and Hicks neutral technological change A(t) and given as:

$$Q(t) = \Omega(t)[1 - \Lambda(t)]A(t)K(t)L(t)^{1-\gamma} \tag{3.4}$$

where, γ is the elasticity of output with respect to capitol which is taken as 0.3. The economic impacts of climate change and investments in CO_2 abatement is represented by damage function Ω(t) and abatement cost function Λ(t) respectively. Damage function assumes that climate damages are proportional to world output and result from surface temperature changes and therefore can be represented as a polynomial function of global mean surface temperature change $T_{AT}(t)$ (^oC rise from 1900):

$$\Omega(t) = 1/[1 + \psi_1 T_{AT}(t) + \psi_2 T_{AT}(t)^2] \tag{3.5}$$

$\psi_1$and $\psi_2$are parameters of damage function and their values are estimated as 0 and 0.0028 respectively through empirical studies. The abatement cost function assumes that abatement cost are proportional to global output and calculates the cost of emission reduction as a polynomial function of emissions reduction rate μ(t):

$$\Lambda(t) = \pi(t)\theta_1(t)\mu(t)^{\theta_2} \tag{3.6}$$

$\pi(t)$ is participation cost markup that is abatement cost with incomplete participation as a fraction of abatement cost with complete participation while $\theta_1(t)$ and θ_2 are parameters of abatement cost function.

Consumption C(t) is defined as the part of output that is not devoted to Investment I(t):

$$C(t) = Q(t) - I(t). \tag{3.7}$$

Thus per capita consumption c(t) can be given as:

$$c(t) = C(t)/L(t). \tag{3.8}$$

Investment at any period contributes to capitol stock at the beginning of next period and depreciates at a constant rate (δ_k):

$$K(t) = I(t-1) + (1- \delta_k)K(t-1). \tag{3.9}$$

Uncontrolled industrial emissions are obtained by multiplying exogenously determined carbon intensity of economic activity $\sigma(t)$ to the total world output:

$$E_{Ind}(t) = \sigma(t)[1-\mu(t)]A(t)K(t)^{\gamma}L(t)^{(1-\gamma)}. \tag{3.10}$$

DICE model assumes that total resources of carbon fuel are limited *CCum* and puts a constraint on the total emissions:

$$CCum \geq \sum_{t=0}^{Tmax} E_{Ind}(t). \tag{3.11}$$

Tmax is the time period for which the model will be executed (first 600 years). However, a study period of only 200 years is taken as the system reaches equilibrium under constat forcing over this time period. The total CO_2 emission is thus given as sum of industrial and land-use (deforestation, landslides etc.) emissions:

$$E(t) = E_{Ind}(t) + E_{Land}(t). \tag{3.12}$$

3.2 THE CARBON CYCLE MODEL

Emission of CO_2 by humans increase the atmospheric CO_2 stock (M_{AT}). DICE models the global mean carbon cycle by a three reservoir model. The three reservoirs for carbon are, the atmosphere, a quickly mixing reservoir in upper oceans and biosphere, and the deep ocean. DICE uses a first order, linear, three box model (reservoir representing boxes) to model the effects of anthropogenic emissions on global mean carbon cycle. CO_2 stock in a reservoir at the beginning of time period t is given as the sum CO_2 stock at period (t-1), amount of CO_2 added directly to the reservoir during period (t-1) and additional CO_2 added as a result of mixing between the two reservoirs. It is mathematically represented as:

$$M_{AT}(t) = E(t-1) + \emptyset_{11} M_{AT}(t-1) + \emptyset_{21} M_{UP}(t-1), \qquad (3.13)$$

$$M_{UP}(t) = \emptyset_{22} M_{UP}(t-1) + \emptyset_{32} M_{Lo}(t-1) + \emptyset_{12} M_{AT}(t-1), \qquad (3.14)$$

$$M_{Lo}(t) = \emptyset_{33} M_{Lo}(t-1) + \emptyset_{23} M_{UP}(t-1). \qquad (3.15)$$

where, $M_{AT}(t)$, $M_{UP}(t)$, and $M_{Lo}(t)$ represent the mass of carbon in reservoir for atmospheric, upper oceans, and lower oceans respectively. $\emptyset_{ij}$ are parameters of carbon cycle and refer to transfer rates of CO_2 between reservoirs.

3.3 THE CLIMATE MODEL

The net radiative forcing F(t) due to CO_2 concentration above pre-industrial level (M_{AT}(1750)) is given as:

$$F(t) = F_{2xCO_2}\left\{log_2\left[\frac{M_{AT}(t)}{M_{AT}(1750)}\right]\right\} + F_{EX}(t) \qquad (3.16)$$

F_{2xCO_2} is the radiative forcing for a doubling of CO_2 concentration and is assumed to be 3.8 W/m^2. $F_{EX}(t)$ represents the forcing of non-CO_2 GHGs and negative forcing due to aerosols.

DICE uses a simple two box climate model that provides a reasonable approximation of climate change response to anthropogenic forcing:

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{Lo}(t-1)]\} \quad (3.17)$$

$$T_{Lo}(t) = T_{Lo}(t-1) + \xi_4[T_{AT}(t-1) - T_{Lo}(t-1)] \quad (3.18)$$

$T_{AT}(t)$ and $T_{Lo}(t)$ increase in global mean surface temperature and temperature of lower oceans from 1990. ξ_i are parameters of climate equation.

3.4 CHANGES MADE TO DICE

In order to incorporate SRM in DICE, forcing equation (3.16) is modified for the inclusion of an additional forcing component $SRM(t)$ (Bickel and Lane, 2009). It represents the amount of negative forcing due to solar radiation management.

$$F(t) = F_{2xCO_2}\left\{log_2\left[\frac{M_{AT}(t)}{M_{AT}(1750)}\right]\right\} + F_{EX}(t) - SRM(t) \quad (3.19)$$

In this report, effects of applying SRM for unplanned durations are studied. Application of SRM leads to negative forcing and thereby a decrease in the global warming when applied for a long time. But, in case, due to unforeseen circumstances if SRM is stopped it can lead to a rapid rise in temperature which in turn will cause some damage. This report study the damage caused due to abruptly stopping SRM after few decade of its deployment. This damage is calculated in two phases. In the first phase, optimization model is executed in GAMS with the assumption that SRM is applied forever. This gives the planned emission control rates μ(t) which the society should implement for each decade. These planned emission control rates will act as additional input for second phase optimization. Let’s say SRM application has to be stopped after *x* periods of its deployment which is not known in advance. Thus, the society will be using the planned emission control rates obtained from earlier optimization and need to improvise when SRM is stopped. This is done in second phase wherein total utility is again maximized but the values of μ(t), for the time periods *x* when SRM is applied, are fixed at levels obtained from first phase. In order to fix the value of emission control rate in GAMS “.fx” suffix was used. So for fixing emission control rate (denoted as miu in GAMS),

miu.fx(“Time Period”) = “Corresponding value obtained from first phase”

is added for each time period SRM was used. The model with these additional constraints in then optimized to find the control rates, temperature change pattern, damage and abatement, etc. for rest of the time periods. Analysis and comparison of the results is done to understand the consequences of unpredictable turning off of SRM.

Damage function used in DICE models damage as a polynomial function of increase in temperature. However, it may fail to capture the damage which can result due to rapid change in temperature (Geos et al. 2008). Thus, in this research, effects of turning off of SRM are also studied using a rate dependent damage function (Lempert et al. 2000). (Note: This study is done in addition to study with DICE's damage function)

$$D(t) = \tanh\left(\alpha_1\left[\frac{\Delta\overline{T}_5(t)}{3℃}\right]^{\eta_1} + \alpha_2\left[\frac{\Delta T(t)-\Delta\overline{T}_{30}(t)}{0.35℃}\right]^{\eta_2}\right) \quad (3.20)$$

Here D(t) measures the climate change damage as a fraction of gross world output, $\Delta T(t)$ is the global mean surface temperature change, $\Delta\overline{T}_5(t)$ and $\Delta\overline{T}_{30}(t)$ are five year running average of $\Delta T(t)$ respectively, α_1 and α_2 are scaling factors and η_1 and η_2 are exponents that determine the non-linearity of the relationship. First term in the equation represents the economic damages due to change in global mean surface temperature and is similar to power law functions used in literature for damage models. The second term represents the climate damage due to long time climate variations which society and ecosystem take time to adapt. Hyperbolic tangent constrains the variability within range of GWP.

CHAPTER 4

4.0 COST-BENEFIT ANALYSIS OF SRM IMPLEMENTATION

This chapter contains a cost benefit analysis of abrupt turning off of SRM. Three strategies, i.e., deployment of negative SRM forcing of 1 W/m^2, 2 W/m^2 and 3 W/m^2 for different time frames varying from 20 years to 200 years and starting from 2025 has been analyzed. These three strategies are named as SRM 1, SRM 2 and SRM 3 respectively. It should be kept in mind that time frame of SRM deployment is not known in advance. In ideal scenario, society should use it forever. However, due to unforeseen circumstances if SRM has to be turned off, then society will have to readjust the emissions and controls to cope up with that. The damage due to such a situation is analyzed using a two phase optimization model discussed in Chapter 3. The optimization is done using CONOPT solver in GAMS. The results of such SRM implementation for unplanned time frame are compared against optimal controls (optimal GHG emissions) with no SRM and against the ideal case with optimal control and SRM for a long time. In addition, DICE model with two different damage functions are separately analyzed and to avoid any confusion in presentation of results, they are grouped under different sections.

4.1 DICE DAMAGE FUNCTION

We first start with comparing reduction in NPV of damage and abatement obtained using optimal controls with SRM and optimal controls without SRM against time frame of SRM deployment (Figure 4.1). It can be seem from the Figure, the net difference in NPV (NPV of damage and abatement without SRM – NPV with SRM) is always positive for various time frames of SRM deployment suggesting that short-term SRM application is profitable than not using SRM at all. Figure 4.1 also shows that net profit of using SRM increases with increase in amount of forcing as well as with increase in time of its deployment. Thus, in the ideal case SRM implementation should be continued once deployed. But, even if it has to be stopped, world will be better off than not using it at all.

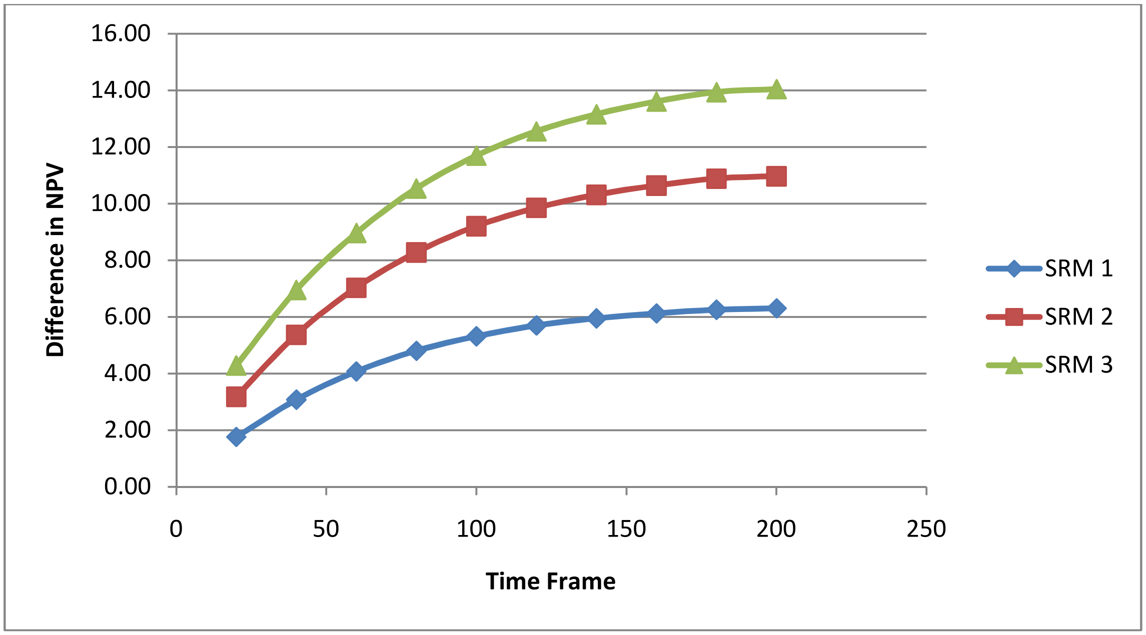

Figure 4.1 Net reductions in NPV of damage and abatement due to SRM implementation for different time frames compared to not using SRM at all

Maximum increase in mean temperature of earth surface varies due to abrupt turning off of SRM as shown in Figure 4.2. Different values of SRM forcing show different tendencies. On one hand, mean surface temperature with SRM1 increases when it is stopped after a short time (20 - 100 years) and goes down with increase in time of its deployment. For SRM2, maximum mean surface temperature increases at first and then goes down with increase in term of its deployment; however, the decrease is much less compared to SRM1. SRM3 shows a totally different trend with maximum mean surface temperature increasing with increase in time of deployment indicating that abrupt stopping of SRM3 may cause a net increase in temperature than not using it. It is also noted that maximum temperature increase is always more than Optimal Control case (SRM0) when SRM2 and SRM3 are used.

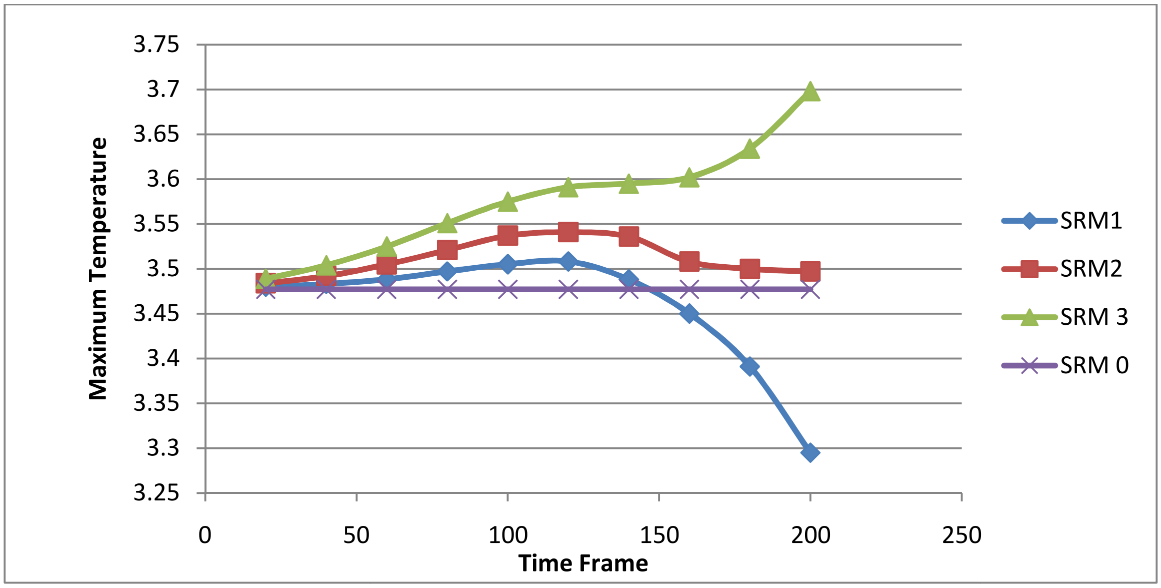

Figure 4.2 Maximum Increase in Mean Surface Temperature vs. Time Frame of SRM deployment

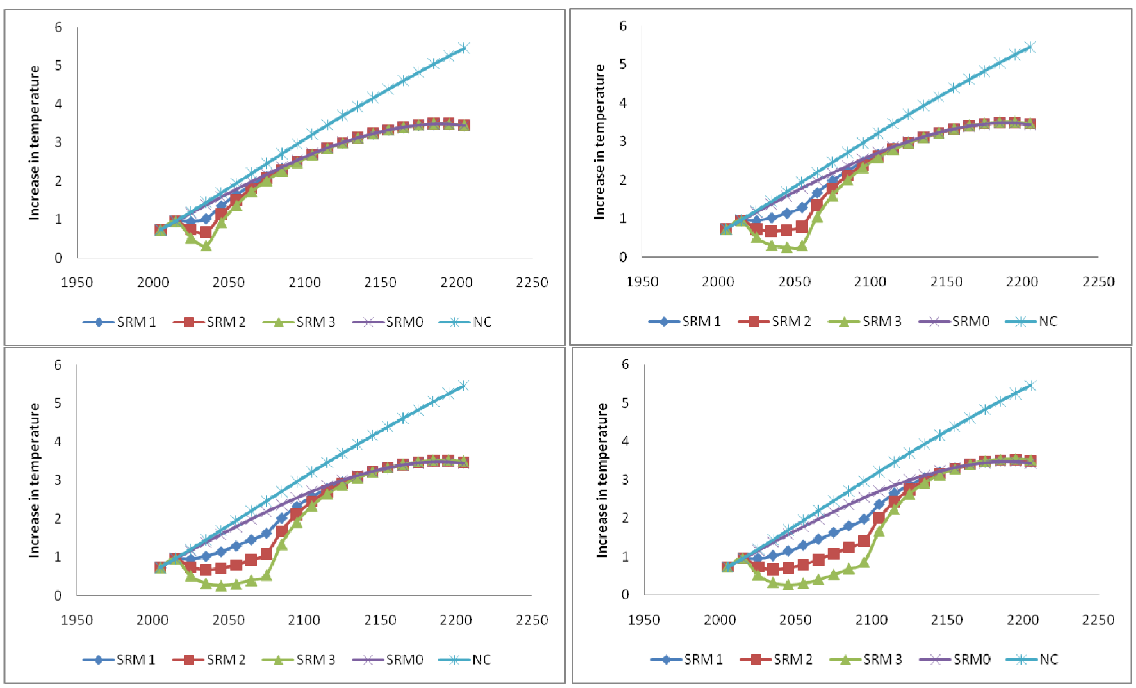

Figure 4.3 Increase in global mean surface temperature Vs. Time when SRM is abruptly stopped after 20 years (top-left), 40 years (top-right), 60 years (bottom-left) and 80 (bottom-right) years of deployment

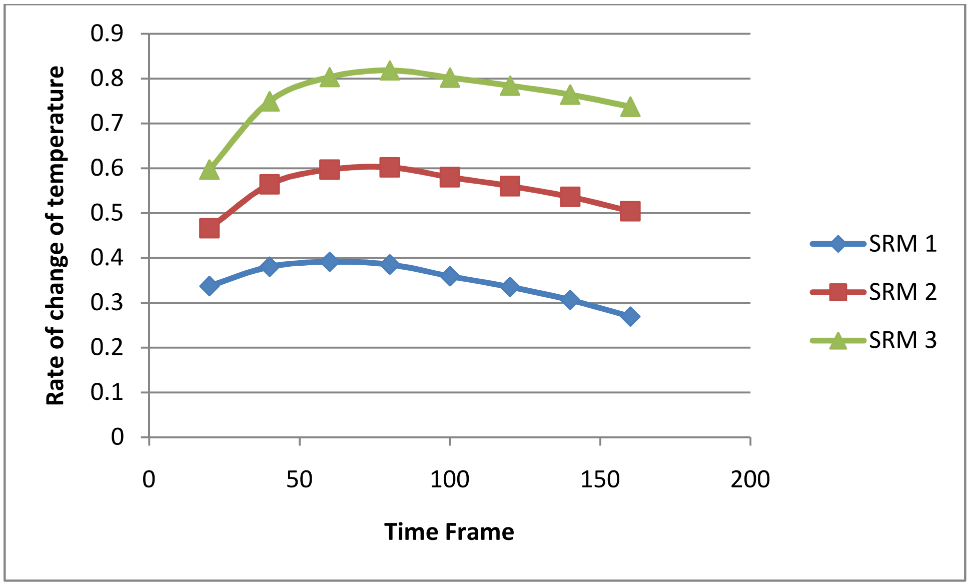

Figure 4.4 Increase in global mean surface temperature just after discontinuing SRM

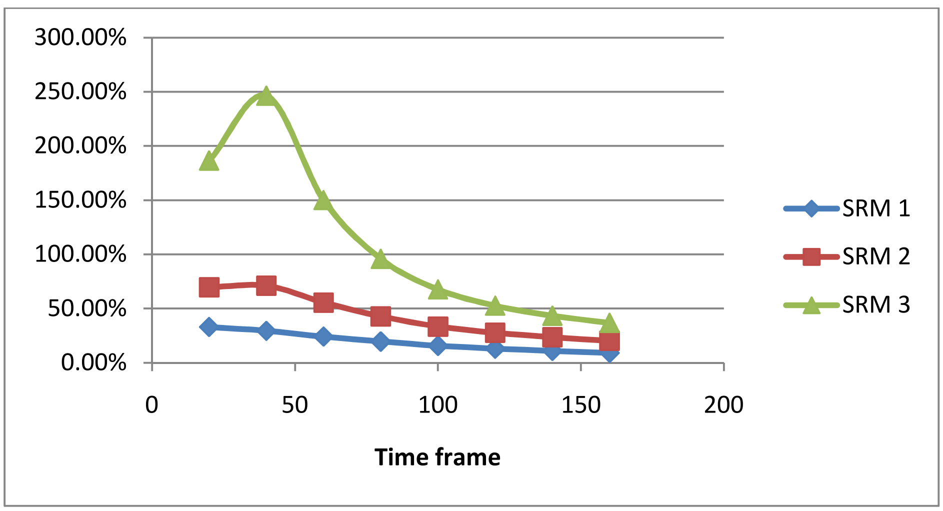

Figure 4.5 Percentage increase in surface temperature when SRM is abruptly stopped

Figure 4.3 shows the increase in global mean surface temperature over the decades when SRM application is abruptly halted after 20, 40, 60 and 80 years. The mean surface temperature increase after 200 years for all the cases is around 3.5^{o}C while Wigley (2006) suggested an increase of 2.2^{o}C for low values of forcing. This indicates that DICE climate model is doing a good job in estimating the increase in temperature and maybe overestimating a little bit. Figure 4.4 and 4.5 describes the relationship between increase in temperature in the next decade after SRM is turned off versus time frame of SRM application. Higher the amount of negative forcing, higher is the increase in temperature after turning it off. The absolute increase in temperature is not much different for different values of forcing and is around 0.34 and 0.59 when SRM1 and SRM2 are abruptly stopped after 20 years. However, as shown in Figure 4.5, the percentage increase in temperature is significantly different for different values of forcing specially for short term SRM application.

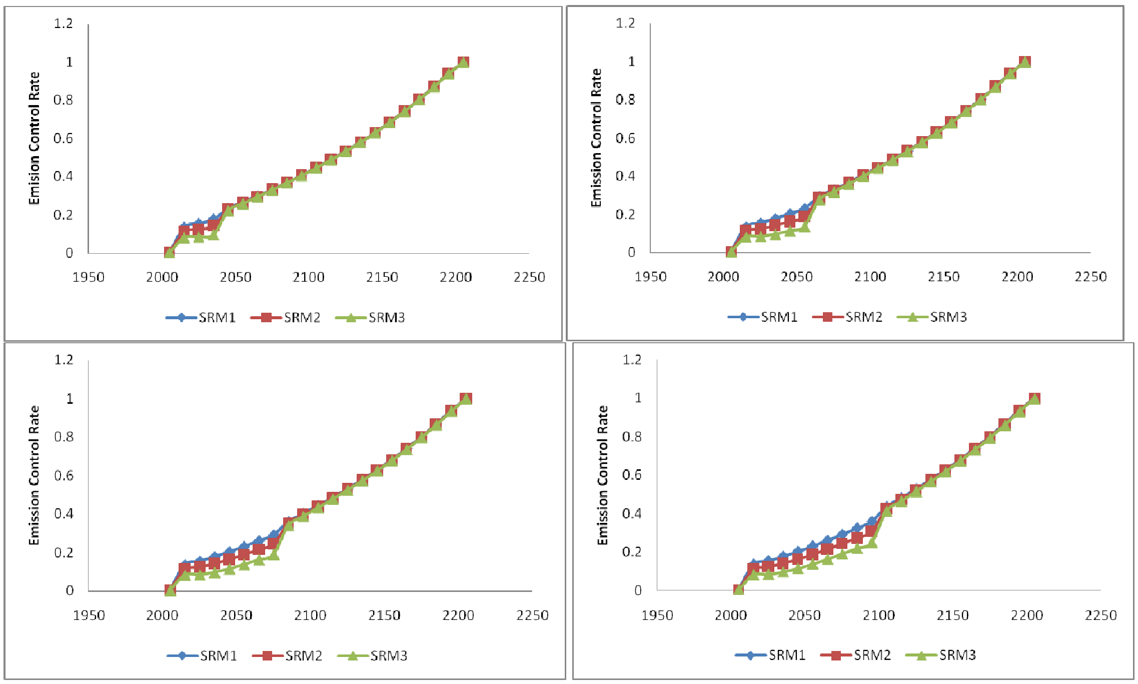

Figure 4.6 Emission Control Rate Vs. Time when SRM is abruptly stopped after 20 years (top-left), 40 years (top-right), 60 years (bottom-left) and 80 (bottom-right) years of deployment

Next, we study the changes in emission control rate. Figure 4.6 shows the variation in emission control rate with time for different values of negative forcing. Similar to temperature, emission control rate increase rapidly when SRM is turned off (Figure 4.7). However, unlike temperature, absolute increase in emission control rate is higher with increase in time of SRM deployment indicating that sudden stopping of SRM after its prolonged use will require more stringent controls. It should be noted that these emission control rates are still lower than those obtained using DICE with optimal controls. The corresponding percentage changes in emission control rate are shown in Figure 4.8.

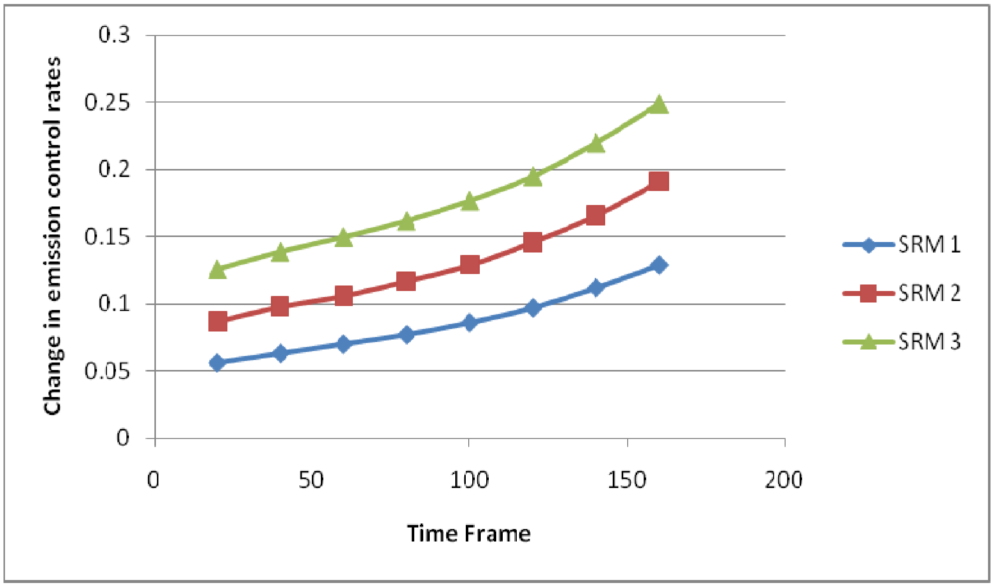

Figure 4.7 Change in emission control rates just after turning off of SRM

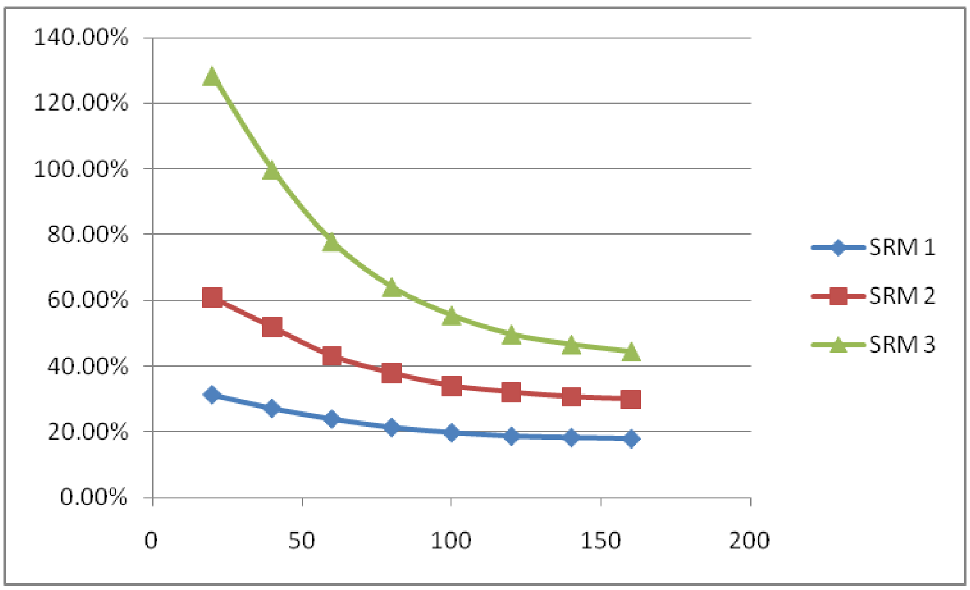

Figure 4.8 Percentage change in emission control rate just after turning off of SRM

Variation in carbon taxes with time for different values of SRM when abruptly halted after different time frames are shown in Figure 4.9. Relationship between change in carbon tax and unplanned turnoff of SRM is shown in Figure 4.10. Figure shows an increase in carbon tax as the SRM is switched off. Figure also portrays that longer the duration of SRM use, higher is the rise in carbon tax after it is stopped. This is explained in terms of increased emissions with SRM. When SRM is applied, DICE increases emissions to increase productivity as negative effects of emissions are balanced by SRM. Longer is the duration of SRM deployment, higher is the amount of CO_2 concentration. Therefore, when SRM is turned off abruptly, model tries to lower the emissions and there is a high increase in carbon tax and emission control rate.

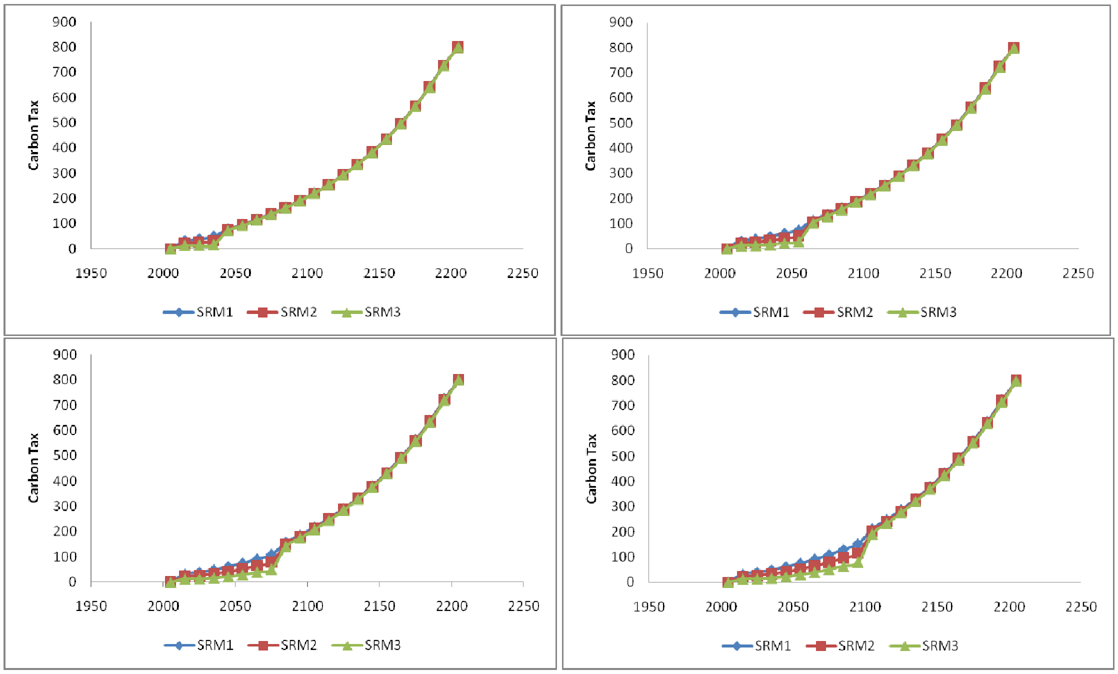

Figure 4.9 Carbon Tax Vs. Time when SRM is abruptly stopped after 20 years (top-left), 40 years (top-right), 60 years (bottom-left) and 80 (bottom-right) years of deployment

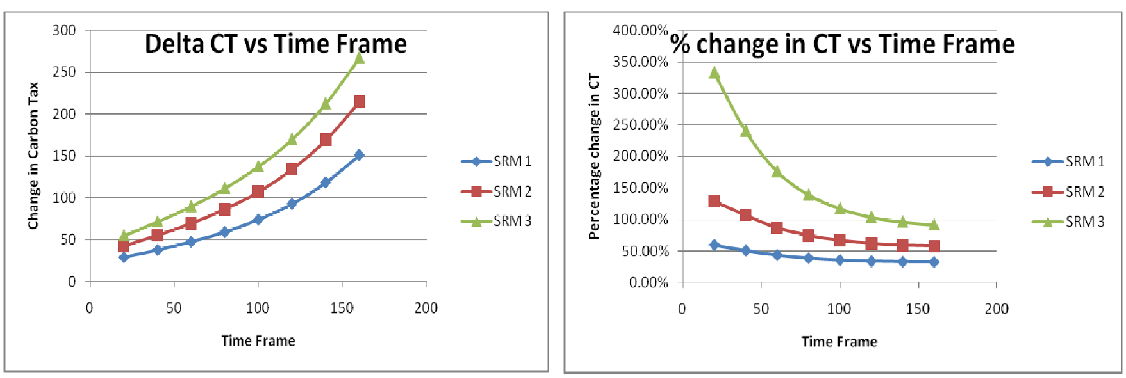

Figure 4.10 Absolute and %age change in Carbon Tax after abrupt turn off of SRM

From the above analysis, it is evident that once SRM is applied, it is in best interest to use it forever. However, in case it has to be stopped due to uncontrollable reasons, the net benefits it will provide are higher than not using this technique at all. It decreases the net NPV of damage and abatement, lowers the global mean surface temperature and delays a given emission reduction level or carbon tax by decades depending upon the period of its deployment.

4.2 LEMPERT'S DAMAGE FUNCTION

This section contains result using Lempert's damage function (Lempert et al. 2000, Geos et al., 2008) within DICE model. DICE damage function is replaced with this function and parameters suggested by Geos et al. (2008) are used[2]. The purpose of using this damage function is its sensitivity to rate of change of temperature. When SRM is turned off abruptly, it causes a rapid increase in temperature. Damage function used in DICE calculates damage only on the basis of increase in mean surface temperature without any consideration to how rapid the rise is. However, one important drawback with Lempert's damage function is the fact that it penalizes for any change in temperature i.e. it also penalizes for a decrease in temperature. High level of SRM forcing (2 W/m^2 and 3 W/m^2) results in initial cooling which is penalized by this damage function. Therefore, we have only analyzed SRM forcing of 1 W/m^2.

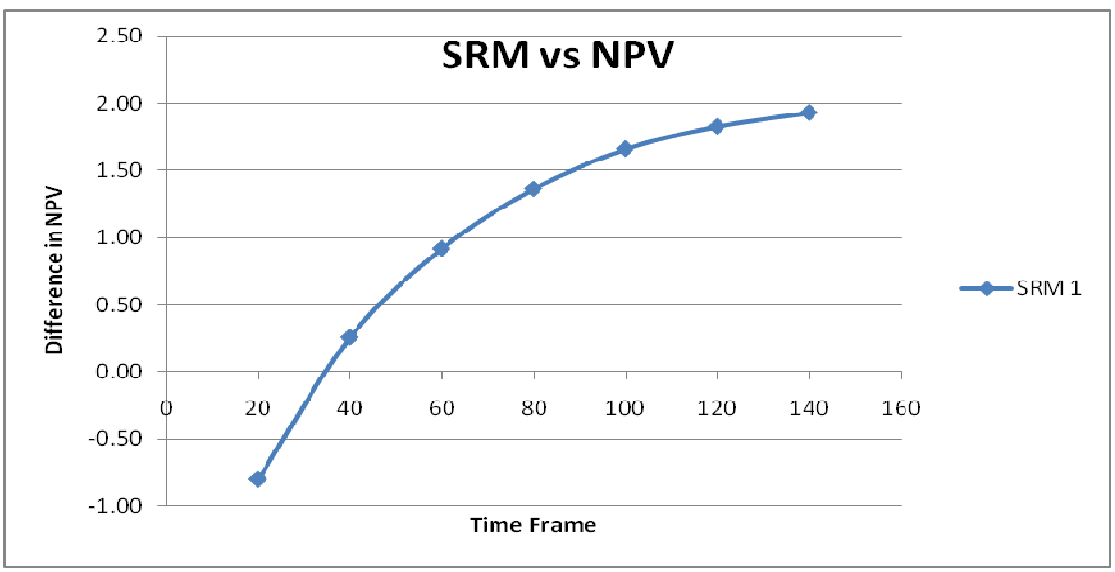

Figure 4.11 Net decrease in NPV of damage and abatement when SRM1 is applied

[2] The way damage function is integrated with DICE model is based on Author's understanding and comprehension of Lempert et al. (2000) and Geos et al. (2008)

As shown in Figure 4.11, the net decrease (compared to optimal controls with no SRM) in NPV of climate damage and abatement cost when SRM1 is applied is positive for all the time frames except when it is stopped 30 or less years after its deployment.

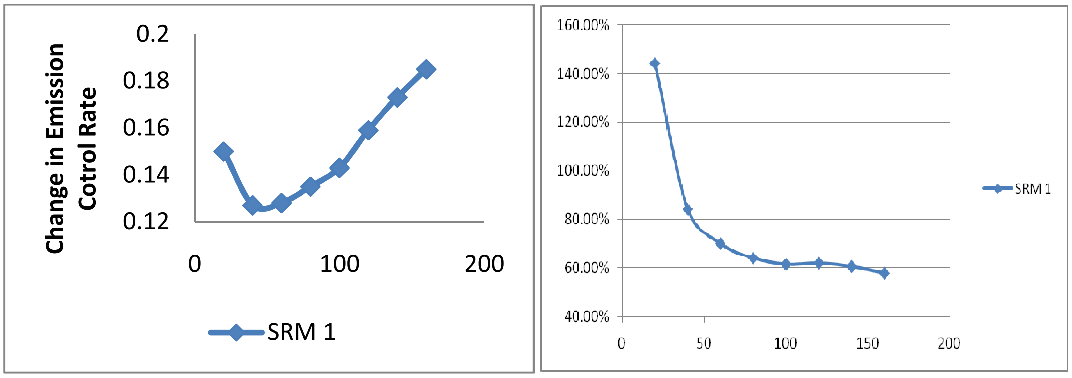

Figure 4.12 Absolute and percentage change in emission control rate just after SRM1 is abruptly stopped

The plot of change in emission control rate (Figure 4.12) vs time frame of SRM deployment is quite different from the plot obtained using DICE damage function. When DICE damage function is used, change in emission control rate follows an increasing trend with increase in time frame of SRM application. However, it is not true when Lempert's damage function is used and the curve shows an initial decreasing trend followed by an increasing trend. The percentage change in emission control rate, though, is always decreasing with increase in time frame of SRM deployment.

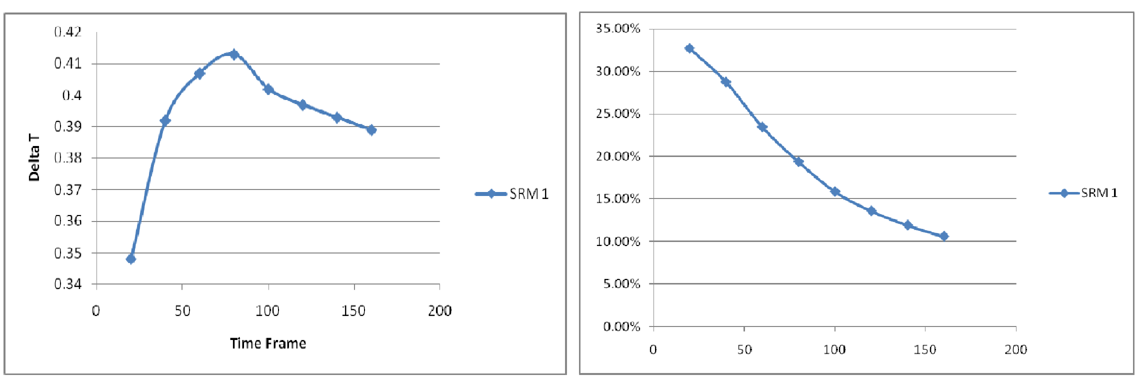

Figure 4.13 Absolute and percentage increase in temperature just after SRM is abruptly stopped

Finally, Figure 4.13 shows the increase in temperature due to unplanned switching off of SRM after given decades of its deployment. The results clearly show a rapid increase in temperature but the damage caused due to this increase could not offset the benefits as shown in Figure 4.11.

CHAPTER 5

5.0 CONCLUSIONS

The objective of the analysis was to study the risks of abrupt ending of SRM. The cost benefit analysis shows that abrupt ending of SRM will not be as profitable as using it forever but the society will still benefit compared to not using it at all. However, this analysis is limited as it is based on numerous assumptions and relies on numbers found in existing literature and existing climate change models. In addition, there still remain many uncertainties regarding the impact of SRM on regional climate. The impact of SRM on precipitation levels and ozone levels, methods to achieve desired levels of forcing, possible side effects of SRM etc. are some of the issues worth further investigation before actual deployment of SRM.

5.1 RISK ASSOCIATED WITH GEOENGINEERING OPTIONS

Geoengineering options can reduce the pressure on society to reduce CO_2 emissions. This can lead to other harmful effects besides global warming. Our analysis also showed that when SRM is applied, emission and CO_2 concentration increases. This can affect the hydrological cycle and food supply of developing countries preset in Asia and Africa. Increased level of CO_2 and sulfur in atmosphere will increase the rate of ocean acidification thus causing serious disruption of marine ecosystem. The effects on corals, shellfish and eventually the entire marine life would be disastrous. Presence of sulfate aerosols would raise temperature for chlorine activation over 200K expanding both vertically and horizontally the regions of polar ozone depletion. SRM systems are unlikely to perfectly reverse all climate consequences of greenhouse gases and could introduce new changes in regional or seasonal climate.

APPENDIX A: GAMS CODE

```
$ontext
DICE delta version 8
July 17, 2008.
This version is used for the DICE book, A Question of Balance (YUP, 2008).
We have included only the base, Hotelling, and optimal runs.
Exclude statements are removed so that it can run as a self-contained program.
Created September 5, 2008.

Note that this can be loaded into a data reading program,

J. Eric Bickel Modified
July 2, 2009
-- I added SRM(T), AC(T), and a temperature constraint.
SRM and AC need to be zeroed and temperature constraint set equal to 20 in order to
get DICE Optimal results
-- I also added the discount rate parameters to match the Stern Review
-- Run the model once to get the optimal value of emission control rate when SRM is applied evenly
-- Assume due to some crcumstances SRM has to stop after few years of its implememntation, run the
program again, fixing emission control rate to study change
-- Only for SRM 1

Shubham Agrawal Modified
December 2, 2009
-- I fixed the values of emission control rates
-- Changed DICE damage function to Lempert's Damage function
-- MOdified damage function only works for SRM1 not for SRM2 and SRM3

$offtext

SETS  T          Time periods          /1*60/ ;

SCALARS

** Preferences
** JEB: Used to match Nordhaus' Stern discounting test
**B_ELASMU   Elasticity of marginal utility of consumption    /  1.000001    /
**B_PRSTP    Initial rate of social time preference per year   / .001    /

B_ELASMU   Elasticity of marginal utility of consumption    /  2.0    /
B_PRSTP    Initial rate of social time preference per year   / .015    /
```

** Population and technology
POP0 2005 world population millions /6514 /
GPOP0 Growth rate of population per decade /.35 /
POPASYM Asymptotic population / 8600 /
A0 Initial level of total factor productivity /.02722 /
GA0 Initial growth rate for technology per decade /.092 /
DELA Decline rate of technol change per decade /.001 /
DK Depreciation rate on capital per year /.100 /
GAMA Capital elasticity in production function /.300 /
Q0 2005 world gross output trill 2005 US dollars /61.1 /
K0 2005 value capital trill 2005 US dollars /137. /

** Emissions
SIG0 CO2-equivalent emissions-GNP ratio 2005 /.13418 /
GSIGMA Initial growth of sigma per decade /-.0730 /
DSIG Decline rate of decarbonization per decade /.003 /
DSIG2 Quadratic term in decarbonization / .000 /
ELAND0 Carbon emissions from land 2005(GtC per decade) / 11.000 /

** Carbon cycle
MAT2000 Concentration in atmosphere 2005 (GtC) /808.9 /
MU2000 Concentration in upper strata 2005 (GtC) /1255 /
ML2000 Concentration in lower strata 2005 (GtC) /18365 /
b11 Carbon cycle transition matrix /0.810712 /
b12 Carbon cycle transition matrix /0.189288 /
b21 Carbon cycle transition matrix /0.097213 /
b22 Carbon cycle transition matrix /0.852787 /
b23 Carbon cycle transition matrix /0.05 /
b32 Carbon cycle transition matrix /0.003119 /
b33 Carbon cycle transition matrix /0.996881 /
*Added
DEL0 initial value of Del(T) /0.2 /
DELT0 initial value of Delt(T) /0.2 /
DELT2 second decade value of DELT(T) /0.2 /
** Climate model
T2XCO2 Equilibrium temp impact of CO2 doubling oC / 3 /
FEX0 Estimate of 2000 forcings of non-CO2 GHG / -.06 /
FEX1 Estimate of 2100 forcings of non-CO2 GHG / 0.30 /
TOCEAN0 2000 lower strat. temp change (C) from 1900 /.0068 /
TATM0 2000 atmospheric temp change (C)from 1900 /.7307 /
C1 Climate-equation coefficient for upper level /.220 /
C3 Transfer coeffic upper to lower stratum /.300 /
C4 Transfer coeffic for lower level /.050 /
FCO22X Estimated forcings of equilibrium co2 doubling /3.8 /

** Climate damage parameters calibrated for quadratic at 2.5 C for 2105

```
* A1      Damage intercept                        / 0.00000    /
*A2      Damage quadratic term                     /  0.0028388 /
 A3      Damage exponent                          / 2.00      /
 A1      alpha 1                             /5.4e-03/
 A2      alpha 2                             /3.3e-04/
 neta1                                  /2/
 neta2                                  /4/
** Abatement cost
 EXPCOST2   Exponent of control cost function             /2.8   /
 PBACK      Cost of backstop 2005 000$ per tC 2005         /1.17  /
 BACKRAT    Ratio initial to final backstop cost           / 2    /
 GBACK      Initial cost decline backstop pc per decade     /.05   /
 LIMMIU     Upper limit on control rate                  / 1    /

** Participation
 PARTFRACT1  Fraction of emissions under control regime 2005 /1      /
 PARTFRACT2  Fraction of emissions under control regime 2015 /1      /
 PARTFRACT21 Fraction of emissions under control regime 2205 /1      /
 DPARTFRACT  Decline rate of participation                 /0      /

** Availability of fossil fuels
 FOSSLIM  Maximum cumulative extraction fossil fuels        / 6000  /

** Scaling and inessential parameters
  scale1 Scaling coefficient in the objective function      /194    /
  scale2 Scaling coefficient in the objective function      /381800 / ;

* Definitions for outputs of no economic interest
SETS
     TFIRST(T)
     TSECOND(T) added
     TLAST(T)
     TEARLY(T)
     TLATE(T);

PARAMETERS
  L(T)         Level of population and labor
  AL(T)         Level of total factor productivity
  SIGMA(T)      CO2-equivalent-emissions output ratio
  R(T)         Instantaeous rate of social time preference
  RR(T)         Average utility social discount rate
  GA(T)         Growth rate of productivity from 0 to T
  FORCOTH(T)    Exogenous forcing for other greenhouse gases
  GL(T)         Growth rate of labor 0 to T
  GCOST1        Growth of cost factor
  GSIG(T)       Cumulative improvement of energy efficiency
```

```
 ETREE(T)     Emissions from deforestation
 COST1(t)     Adjusted cost for backstop
 PARTFRACT(T)  Fraction of emissions in control regime
 AA1          Variable A1
 AA2          Variable A2
 AA3          Variable A3
 ELASMU       Variable elasticity of marginal utility of consumption
 PRSTP        Variable nitial rate of social time preference per year
 LAM          Climate model parameter
 Gfacpop(T)   Growth factor population ;

PARAMETERS
 L(T)         Level of population and labor
 AL(T)        Level of total factor productivity
 SIGMA(T)     CO2-equivalent-emissions output ratio
 RR(T)        Average utility social discount factor
 GA(T)        Growth rate of productivity from 0 to T
 FORCOTH(T)   Exogenous forcing for other greenhouse gases
 GL(T)        Growth rate of labor 0 to T
 GCOST1       Growth of cost factor
 GSIG(T)      Cumulative improvement of energy efficiency
 ETREE(T)     Emissions from deforestation
 COST1(t)     Adjusted cost for backstop
 PARTFRACT(T)  Fraction of emissions in control regime
 AA1          Variable A1
 AA2          Variable A2
 AA3          Variable A3
 ELASMU       Variable elasticity of marginal utility of consumption
 PRSTP        Variable nitial rate of social time preference per year
 LAM          Climate model parameter
 Gfacpop(T)   Growth factor population ;

PARAMETER SRM(T)
     /1      0
2     0
3     1
4     1
5     1
6     1
7     1
8     1
9     1
10     1
11     1
12     1
13     1
```

14	1
15	1
16	1
17	1
18	1
19	1
20	1
21	1
22	1
23	0
24	0
25	0
26	0
27	0
28	0
29	0
30	0
31	0
32	0
33	0
34	0
35	0
36	0
37	0
38	0
39	0
40	0
41	0
42	0
43	0
44	0
45	0
46	0
47	0
48	0
49	0
50	0
51	0
52	0
53	0
54	0
55	0
56	0
57	0
58	0
59	0

```
60      0
/;

PARAMETER AC(T)
        /1 0
        2 0
        3 0
        4 0
        5 0
        6 0
        7 0
        8 0
        9 0
        10 0
        11 0
        12 0
        13 0
        14 0
        15 0
        16 0
        17 0
        18 0
        19 0
        20 0
        21 0
        22 0
        23 0
        24 0
        25 0
        26 0
        27 0
        28 0
        29 0
        30 0
        31 0
        32 0
        33 0
        34 0
        35 0
        36 0
        37 0
        38 0
        39 0
        40 0
        41 0
        42 0
```

```
        43 0
        44 0
        45 0
        46 0
        47 0
        48 0
        49 0
        50 0
        51 0
        52 0
        53 0
        54 0
        55 0
        56 0
        57 0
        58 0
        59 0
        60 0
/;

* Unimportant definitions to reset runs
TFIRST(T) = YES$(ORD(T) EQ 1);
*added
TSECOND(T) = YES$(ORD(T) EQ 2);
TLAST(T)  = YES$(ORD(T) EQ CARD(T));
TEARLY(T) = YES$(ORD(T) LE 20);
TLATE(T)  = YES$(ORD(T) GE 21);
AA1 = A1;
AA2 = A2;
AA3 = A3;
ELASMU = B_ELASMU;
PRSTP  = B_PRSTP;

b11 = 1 - b12;
b21 = 587.473*B12/1143.894;
b22 = 1 - b21 - b23;
b32 = 1143.894*b23/18340;
b33 = 1 - b32 ;


* Important parameters for the model
LAM     = FCO22X/ T2XCO2;
Gfacpop(T) =   (exp(gpop0*(ORD(T)-1))-1)/exp(gpop0*(ORD(T)-1));
L(T)=POP0* (1- Gfacpop(T))+Gfacpop(T)*popasym;
ga(T)=ga0*EXP(-dela*10*(ORD(T)-1));
al("1") = a0;
```

```
LOOP(T, al(T+1)=al(T)/((1-ga(T))););
gsig(T)=gsigma*EXP(-dsig*10*(ORD(T)-1)-dsig2*10*((ord(t)-
1)**2));sigma("1")=sig0;LOOP(T,sigma(T+1)=(sigma(T)/((1-gsig(T+1)))););
cost1(T) = (PBACK*SIGMA(T)/EXPCOST2)* ( (BACKRAT-1+ EXP (-gback* (ORD(T)-1) ) )/BACKRAT);
ETREE(T) = ELAND0*(1-0.1)**(ord(T)-1);
RR(t)=1/((1+prstp)**(10*(ord(T)-1)));
FORCOTH(T)= FEX0+ .1*(FEX1-FEX0)*(ORD(T)-1)$(ORD(T) LT 12)+ 0.36$(ORD(T) GE 12);
partfract(t) = partfract21;
PARTFRACT(T)$(ord(T)<25) = Partfract21 + (PARTFRACT2-Partfract21)*exp(-DPARTFRACT*(ORD(T)-2));
partfract("1")= PARTFRACT1;


VARIABLES
 MIU(T)        Emission control rate GHGs
 FORC(T)       Radiative forcing in watts per m2
 TATM(T)       Temperature of atmosphere in degrees C
 TOCEAN(T)     Temperatureof lower oceans degrees C
 MAT(T)        Carbon concentration in atmosphere GtC
 MATAV(T)      Average concentrations
 MU(T)         Carbon concentration in shallow oceans Gtc
 ML(T)         Carbon concentration in lower oceans GtC
 E(T)          CO2-equivalent emissions GtC
 C(T)          Consumption trillions US dollars
 K(T)          Capital stock trillions US dollars
 CPC(T)        Per capita consumption thousands US dollars
 PCY(t)        Per capita income thousands US dollars
 I(T)          Investment trillions US dollars
 S(T)          Gross savings rate as fraction of gross world product
 RI(T)         Real interest rate per annum
 Y(T)          Gross world product net of abatement and damages
 YGROSS(T)     Gross world product GROSS of abatement and damages
 YNET(T)       Output net of damages equation
 DAMAGES(T)    Damages
 ABATECOST(T)  Cost of emissions reductions
 CCA(T)        Cumulative industrial carbon emissions GTC
 PERIODU(t)    One period utility function
* two new variables introduced for implementing Geos et al model
 DEL(T)        Mean Annual Temperature Change in degree C
 DELT(T)       30 year running average of DET(T)
 UTILITY;

POSITIVE VARIABLES MIU, TATM, TOCE, E, MAT, MATAV, MU, ML, Y, YGROSS, C, K, I, CCA ;

EQUATIONS

 CCTFIRST(T)   First period cumulative carbon
```

```
 CCACCA(T)       Cumulative carbon emissions
 UTIL            Objective function
 YY(T)           Output net equation
 YNETEQ(T)       Output net of damages equation
 YGROSSEQ(T)     Output gross equation
 DAMEQ(T)        Damage equation
 ABATEEQ(T)      Cost of emissions reductions equation
 CC(T)           Consumption equation
 KK(T)           Capital balance equation
 KK0(T)          Initial condition for capital
 KC(T)           Terminal condition for capital
 CPCE(t)         Per capita consumption definition
 PCYE(T)         Per capita income definition
 EE(T)           Emissions equation
 SEQ(T)          Savings rate equation
 RIEQ(T)         Interest rate equation
 FORCE(T)        Radiative forcing equation
 MMAT0(T)        Starting atmospheric concentration
 MMAT(T)         Atmospheric concentration equation
 MMATAVEQ(t)     Average concentrations equation
 MMU0(T)         Initial shallow ocean concentration
 MMU(T)          Shallow ocean concentration
 MML0(T)         Initial lower ocean concentration
 MML(T)          Lower ocean concentration
 TATMEQ(T)       Temperature-climate equation for atmosphere
 TATM0EQ(T)      Initial condition for atmospheric temperature
 TOCEANEQ(T)     Temperature-climate equation for lower oceans
 TOCEAN0EQ(T)    Initial condition for lower ocean temperature
 PERIODUEQ(t)    Instantaneous utility function equation
* Two new equations introduced to calculate Del(t) and Delt(t)
 DDEL0(T)    Initial condition for Del(T)
 DDEL(T)         Equations for calcualting Del(T)
 DDELT0(T)   Initial Cndition for DDel(T)
 DDELT00(T)  Value of DDEL for Second decade
 DDELT(T)        Equation for calcualting DDel(T)
;



** Equations of the model

CCTFIRST(TFIRST).. CCA(TFIRST)=E=0;
CCACCA(T+1)..     CCA(T+1)=E=CCA(T)+ E(T);
KK(T)..           K(T+1) =L= (1-DK)**10 *K(T)+10*I(T);
KK0(TFIRST)..     K(TFIRST) =E= K0;
KC(TLAST)..       .02*K(TLAST) =L= I(TLAST);
```

```
EE(T)..          E(T)=E=10*SIGMA(T)*(1-MIU(T))*AL(T)*L(T)**(1-GAMA)*K(T)**GAMA + ETREE(T);
** Subtracted SRM(T) from the following eqn
FORCE(T)..       FORC(T) =E=  FCO22X*((log((Matav(T)+.000001)/596.4)/log(2)))+FORCOTH(T)-SRM(T);
MMAT0(TFIRST)..    MAT(TFIRST) =E= MAT2000;
MMU0(TFIRST)..     MU(TFIRST)  =E= MU2000;
MML0(TFIRST)..     ML(TFIRST)  =E= ML2000;
** Subtracted AC(T) from the following eqn
MMAT(T+1)..       MAT(T+1)    =E= MAT(T)*b11+MU(T)*b21 + E(T) - AC(T);
MMATAVEQ(t)..      MATAV(T)    =e= (MAT(T)+MAT(T+1))/2 ;
MML(T+1)..        ML(T+1)     =E= ML(T)*b33+b23*MU(T);
MMU(T+1)..        MU(T+1)     =E= MAT(T)*b12+MU(T)*b22+ML(T)*b32;
TATM0EQ(TFIRST)..  TATM(TFIRST) =E= TATM0;
TATMEQ(T+1)..      TATM(T+1) =E= TATM(t)+C1*(FORC(t+1)-LAM*TATM(t)-C3*(TATM(t)-TOCEAN(t)));
TOCEAN0EQ(TFIRST)..  TOCEAN(TFIRST) =E= TOCEAN0;
TOCEANEQ(T+1)..    TOCEAN(T+1) =E= TOCEAN(T)+C4*(TATM(T)-TOCEAN(T));
YGROSSEQ(T)..   YGROSS(T) =e= AL(T)*L(T)**(1-GAMA)*K(T)**GAMA;
DDEL0(TFIRST)..  DEL(TFIRST) =E= DEL0;
DDEL(T+1)..     DEL(T+1) =E= TATM(T+1) - TATM(T);
DDELT0(TFIRST).. DELT(TFIRST) =E= DELT0;
DDELT00(TSECOND).. DELT(TSECOND) =E= DELT2;
DDELT(T+2)..     DELT(T+2) =E= (DEL(T+2)+DEL(T+1)+DEL(T))/3;
DAMEQ(T)..       DAMAGES(t) =E= YGROSS(T)*100*arctan(a1*(del(t)/3)*(del(t)/3) + a2*((del(t)-
delt(t))/0.35)*((del(t)-delt(t))/0.35)*((del(t)-delt(t))/0.35)*((del(t)-delt(t))/0.35));
YNETEQ(t)..      YNET(T) =E=  YGROSS(T) - YGROSS(T)*100*arctan(a1*(del(t)/3)*(del(t)/3) + a2*((del(t)-
delt(t))/0.35)*((del(t)-delt(t))/0.35)*((del(t)-delt(t))/0.35)*((del(t)-delt(t))/0.35));
*DAMEQ(T)..      DAMAGES(t) =E= YGROSS(T)- YGROSS(T)/(1+aa1*TATM(T)+ aa2*TATM(T)**aa3);
*YNETEQ(T)..     YNET(T) =E=  YGROSS(T)/(1+aa1*TATM(T)+ aa2*TATM(T)**aa3);
ABATEEQ(T)..    ABATECOST(T) =E= (PARTFRACT(T)**(1-
expcost2))*YGROSS(T)*(cost1(t)*(MIU(T)**EXPcost2));
YY(T)..         Y(T) =E=  YGROSS(T)*((1-(PARTFRACT(T)**(1-expcost2))*cost1(t)*(MIU(T)**EXPcost2)))*(1-
100*arctan(a1*(del(t)/3)*(del(t)/3) + a2*((del(t)-delt(t))/0.35)*((del(t)-delt(t))/0.35)*((del(t)-
delt(t))/0.35)*((del(t)-delt(t))/0.35)));
*YY(T)..         Y(T) =E= YGROSS(T)*((1-(PARTFRACT(T)**(1-
expcost2))*cost1(t)*(MIU(T)**EXPcost2)))/(1+aa1*TATM(T)+ aa2*TATM(T)**aa3);
SEQ(T)..        S(T)    =E= I(T)/(.001+Y(T));
RIEQ(T)..       RI(T)   =E= GAMA*Y(T)/K(T)- (1-(1-DK)**10)/10  ;
CC(T)..         C(T)    =E= Y(T)-I(T);
CPCE(T)..       CPC(T)  =E= C(T)*1000/L(T);
PCYE(T)..       PCY(T)  =E= Y(T)*1000/L(T);
PERIODUEQ(T)..  PERIODU(T)  =E=   ((C(T)/L(T))**(1-ELASMU)-1)/(1-ELASMU);
UTIL..          UTILITY =E= SUM(T, 10 *RR(T)*L(T)*(PERIODU(T))/scale1)+ scale2 ;

**  Upper and Lower Bounds: General conditions for stability

K.lo(T)         = 100;
MAT.lo(T)       = 10;
```

```
MU.lo(t)       = 100;
ML.lo(t)       = 1000;
C.lo(T)        = 20;
TOCEAN.up(T)    = 20;
TOCEAN.lo(T)    = -1;
*** TATM.up(t)      = 20;     JEB: Original, Change to 2 for temp limit
TATM.up(t)      = 20;
miu.up(t)       = LIMMIU;
partfract("1")= 0.25372;

* First period predetermined by Kyoto Protocol
miu.fx("1")     = 0.005;

** fixing emission control rate, for SRM = 1, starts at 2025
*miu.fx("2") = 0.065;
*miu.fx("3") = 0.0;
*miu.fx("4") = 0.104;
*miu.fx("5") = 0.132;
*miu.fx("6") = 0.151;
*miu.fx("7") = 0.168;
*miu.fx("8") = 0.183;
*miu.fx("9") = 0.198;
*miu.fx("10") = 0.211;
*miu.fx("11") = 0.223;
*miu.fx("12") = 0.233;
*miu.fx("13") = 0.244;
*miu.fx("14") = 0.257;
*miu.fx("15") = 0.271;
*miu.fx("16") = 0.286;
*miu.fx("17") = 0.302;
*miu.fx("18") = 0.32;
*miu.fx("19") = 0.339;
*miu.fx("20") = 0.36;
*miu.fx("21") = 0.384;
*miu.fx("22") = 0.411;

** fixing emission control rate, for SRM = 2, starts at 2025
*miu.fx("2") = 0.112;
*miu.fx("3") = 0.125;
*miu.fx("4") = 0.143;
*miu.fx("5") = 0.164;
*miu.fx("6") = 0.189;
*miu.fx("7") = 0.216;
*miu.fx("8") = 0.246;
*miu.fx("9") = 0.276;
*miu.fx("10") = 0.309;
```

```
*miu.fx("11") = 0.343;
*miu.fx("12") = 0.379;
*miu.fx("13") = 0.417;
*miu.fx("14") = 0.456;
*miu.fx("15") = 0.498;
*miu.fx("16") = 0.542;
*miu.fx("17") = 0.589;
*miu.fx("18") = 0.638;
*miu.fx("19") = 0.69;
*miu.fx("20") = 0.745;
*miu.fx("21") = 0.802;
*miu.fx("22") = 0.863;

** fixing emission control rate, for SRM = 3, starts at 2025
*miu.fx("2") = 0.083;
*miu.fx("3") = 0.086;
*miu.fx("4") = 0.098;
*miu.fx("5") = 0.116;
*miu.fx("6") = 0.139;
*miu.fx("7") = 0.164;
*miu.fx("8") = 0.192;
*miu.fx("9") = 0.221;
*miu.fx("10") = 0.252;
*miu.fx("11") = 0.284;
*miu.fx("12") = 0.318;
*miu.fx("13") = 0.353;
*miu.fx("14") = 0.391;
*miu.fx("15") = 0.429;
*miu.fx("16") = 0.47;
*miu.fx("17") = 0.513;
*miu.fx("18") = 0.558;
*miu.fx("19") = 0.605;
*miu.fx("20") = 0.654;
*miu.fx("21") = 0.705;
*miu.fx("22") = 0.759;

** Fix savings assumption for standardization if needed
s.fx(t)=.22;

** Cumulative limits on carbon use at 6000 GtC
CCA.up(T) = FOSSLIM;

** Solution options
option iterlim = 99900;
option reslim = 99999;
option solprint = on;
```

```
option limrow = 0;
option limcol = 0;
model CO2 /all/;

* Optimal run
* Solution for optimal run

solve CO2 maximizing UTILITY using nlp ;

* Definition of opt results

Parameters
Year(t)        Date
opt_y(t)
opt_cpc(t)
opt_s(t)
opt_indem(t)
opt_sigma(t)
opt_tatm(t)
opt_mat(t)
opt_tax(t)
opt_ri(t)
opt_rr(t)
opt_al(t)
opt_forcoth(t)
opt_l(t)
opt_etree(t)
opt_yy(t)
opt_cc(t)
opt_miu(t)
opt_wem(t)
opt_ri(t)
opt_dam(t)
opt_abate(t)
opt_mcemis(t)
opt_gwp(t)
opt_utility;

Year(t)        = 2005 +10*(ord(t)-1);
opt_y(t)=y.l(t);
opt_gwp(t) = ynet.l(t);
opt_cpc(t)=cpc.l(t);
opt_s(t)=s.l(t)     ;
opt_indem(t)= e.l(t)-etree(t);;
opt_sigma(t)=sigma(t) ;
opt_tatm(t)=tatm.l(t)  ;
```

```
opt_mat(t)=mat.l(t)     ;
opt_tax(t)=-1*ee.m(t)*1000/(kk.m(t)+.00000000001)       ;
opt_ri(t)=ri.l(t);
opt_rr(t)=rr(t)   ;
opt_al(t)=al(t)    ;
opt_forcoth(t)=forcoth(t);
opt_l(t)=l(t);
opt_etree(t)=etree(t);
opt_yy(t)=yy.m(t)     ;
opt_cc(t)=cc.m(t)      ;
opt_miu(t)=miu.l(t)     ;
opt_wem(t)= e.l(t);
opt_ri(t)=ri.l(t)         ;
opt_dam(t)= damages.l(t);
opt_abate(t) = abatecost.l(t);
opt_mcemis(t)= expcost2*cost1(t)*miu.l(t)**(expcost2-1)/sigma(t)*1000;
opt_utility=utility.l        ;

* Reset for initial conditions

aa1 = a1;
aa2 = a2;
aa3 = a3;

PBACK =  1.17 ;
PARTFRACT1 = 1;
PARTFRACT2 = 1;
PARTFRACT21 = 1;
partfract(t) = partfract21;
cost1(T) = (PBACK*SIGMA(T)/EXPCOST2)* ( (BACKRAT-1+ EXP (-gback* (ORD(T)-1) ) )/BACKRAT);
PARTFRACT(T)$(ord(T)<25) = Partfract21 + (PARTFRACT2-Partfract21)*exp(-DPARTFRACT*(ORD(T)-2));
partfract("1")= PARTFRACT1;

TATM.up(t)  = 10 ;
mat.up(T)= 4000;
miu.up(t)= 1;
miu.lo(t)= .001;
k.lo(t) = 1;
k.up(t) = 1000000;
K0 = 137;
miu.fx("1")=.005;
partfract("1")=       0.25372  ;

* Estimate Hoteling rents
* parameter estimates
```

```
  aa1 = 0;
  aa2 = 0;
solve CO2 maximizing UTILITY using nlp ;

parameters
miuhotel(t)    estimate of Hoteling rents;
miuhotel(t)=miu.l(t);

* Definition of hotelling results

Parameters
Year(t)         Date
hotel_y(t)
hotel_cpc(t)
hotel_s(t)
hotel_indem(t)
hotel_sigma(t)
hotel_tatm(t)
hotel_mat(t)
hotel_tax(t)
hotel_ri(t)
hotel_rr(t)
hotel_al(t)
hotel_forcoth(t)
hotel_l(t)
hotel_etree(t)
hotel_yy(t)
hotel_cc(t)
hotel_miu(t)
hotel_wem(t)
hotel_ri(t)
hotel_dam(t)
hotel_abate(t)
hotel_mcemis(t)
hotel_utility   ;

Year(t)         = 2005 +10*(ord(t)-1);
hotel_y(t)=y.l(t);
hotel_cpc(t)=cpc.l(t);
hotel_s(t)=s.l(t)     ;
hotel_indem(t)= e.l(t)-etree(t);;
hotel_sigma(t)=sigma(t) ;
hotel_tatm(t)=tatm.l(t)  ;
hotel_mat(t)=mat.l(t)     ;
hotel_tax(t)=-1*ee.m(t)*1000/(kk.m(t)+.0000001)       ;
hotel_ri(t)=ri.l(t);
```

```
hotel_rr(t)=rr(t)   ;
hotel_al(t)=al(t)    ;
hotel_forcoth(t)=forcoth(t);
hotel_l(t)=l(t);
hotel_etree(t)=etree(t);
hotel_yy(t)=yy.m(t)     ;
hotel_cc(t)=cc.m(t)      ;
hotel_miu(t)=miu.l(t)     ;
hotel_wem(t)= e.l(t);
hotel_ri(t)=ri.l(t)        ;
hotel_dam(t)= damages.l(t);
hotel_abate(t) = abatecost.l(t);
hotel_mcemis(t)= expcost2*cost1(t)*miu.l(t)**(expcost2-1)/sigma(t)*1000;
hotel_utility=utility.l       ;
* Reset for initial conditions

aa1 = a1;
aa2 = a2;
aa3 = a3;

PBACK =  1.17 ;
PARTFRACT1 = 1;
PARTFRACT2 = 1;
PARTFRACT21 = 1;
partfract(t) = partfract21;
cost1(T) = (PBACK*SIGMA(T)/EXPCOST2)* ( (BACKRAT-1+ EXP (-gback* (ORD(T)-1) ) )/BACKRAT);
PARTFRACT(T)$(ord(T)<25) = Partfract21 + (PARTFRACT2-Partfract21)*exp(-DPARTFRACT*(ORD(T)-2));
partfract("1")= PARTFRACT1;

TATM.up(t)  = 10 ;
mat.up(T)= 4000;
miu.up(t)= 1;
miu.lo(t)= .001;
k.lo(t) = 1;
k.up(t) = 1000000;
K0 = 137;
miu.fx("1")=.005;
partfract("1")=       0.25372  ;


* Base-25per defined as 250 years of no action with miu at Hotelling control rates
* Definition of base_250yr results

* Control statements
MIU.lo("1")=miuhotel("1");
MIU.lo("2")=miuhotel("2");
```

```
MIU.lo("3")=miuhotel("3");
MIU.lo("4")=miuhotel("4");
MIU.lo("5")=miuhotel("5");
MIU.lo("6")=miuhotel("6");
MIU.lo("7")=miuhotel("7");
MIU.lo("8")=miuhotel("8");
MIU.lo("9")=miuhotel("9");
MIU.lo("10")=miuhotel("10");
MIU.lo("11")=miuhotel("11");
MIU.lo("12")=miuhotel("12");
MIU.lo("13")=miuhotel("13");
MIU.lo("14")=miuhotel("14");
MIU.lo("15")=miuhotel("15");
MIU.lo("16")=miuhotel("16");
MIU.lo("17")=miuhotel("17");
MIU.lo("18")=miuhotel("18");
MIU.lo("19")=miuhotel("19");
MIU.lo("20")=miuhotel("20");
MIU.lo("21")=miuhotel("21");
MIU.lo("22")=miuhotel("22");
MIU.lo("23")=miuhotel("23");
MIU.lo("24")=miuhotel("24");
MIU.lo("25")=miuhotel("25");

MIU.up("1")=miuhotel("1");
MIU.up("2")=miuhotel("2");
MIU.up("3")=miuhotel("3");
MIU.up("4")=miuhotel("4");
MIU.up("5")=miuhotel("5");
MIU.up("6")=miuhotel("6");
MIU.up("7")=miuhotel("7");
MIU.up("8")=miuhotel("8");
MIU.up("9")=miuhotel("9");
MIU.up("10")=miuhotel("10");
MIU.up("11")=miuhotel("11");
MIU.up("12")=miuhotel("12");
MIU.up("13")=miuhotel("13");
MIU.up("14")=miuhotel("14");
MIU.up("15")=miuhotel("15");
MIU.up("16")=miuhotel("16");
MIU.up("17")=miuhotel("17");
MIU.up("18")=miuhotel("18");
MIU.up("19")=miuhotel("19");
MIU.up("20")=miuhotel("20");
MIU.up("21")=miuhotel("21");
MIU.up("22")=miuhotel("22");
```

```
MIU.up("23")=miuhotel("23");
MIU.up("24")=miuhotel("24");
MIU.up("25")=miuhotel("25");

solve CO2 maximizing UTILITY using nlp ;

*Output
Parameters
Year(t)        Date
base25_y(t)
base25_cpc(t)
base25_s(t)
base25_indem(t)
base25_sigma(t)
base25_tatm(t)
base25_mat(t)
base25_tax(t)
base25_ri(t)
base25_rr(t)
base25_al(t)
base25_forcoth(t)
base25_l(t)
base25_etree(t)
base25_yy(t)
base25_cc(t)
base25_miu(t)
base25_wem(t)
base25_ri(t)
base25_dam(t)
base25_abate(t)
base25_mcemis(t)
base25_mcemis(t)
base25_utility
base25_k(t) ;

Year(t)        = 2005 +10*(ord(t)-1);
base25_y(t)=y.l(t);
base25_cpc(t)=cpc.l(t);
base25_s(t)=s.l(t)     ;
base25_indem(t)= e.l(t)-etree(t);;
base25_sigma(t)=sigma(t) ;
base25_tatm(t)=tatm.l(t)  ;
base25_mat(t)=mat.l(t)     ;
base25_tax(t)=-1*ee.m(t)*1000/(kk.m(t)+.00000000001)       ;
base25_ri(t)=ri.l(t);
base25_rr(t)=rr(t)   ;
```

```
base25_al(t)=al(t)    ;
base25_forcoth(t)=forcoth(t);
base25_l(t)=l(t);
base25_etree(t)=etree(t);
base25_yy(t)=yy.m(t)     ;
base25_cc(t)=cc.m(t)      ;
base25_miu(t)=miu.l(t)     ;
base25_wem(t)= e.l(t);
base25_ri(t)=ri.l(t)         ;
base25_dam(t)= damages.l(t);
base25_abate(t) = abatecost.l(t);
base25_mcemis(t)= expcost2*cost1(t)*miu.l(t)**(expcost2-1)/sigma(t)*1000;
base25_utility=utility.l       ;
base25_mcemis(t) = expcost2*cost1(t)*miu.l(t)**(expcost2-1)/sigma(t)*1000;
base25_k(t) = k.l(t);


* Output of all runs in one put file


*$include put_opt_early.gms

File all_d07e;
all_d07e.pc=5;
all_d07e.pw=250;
Put all_d07e;
Put / "Optimal run (economic optimum)";
Put / "year";
Loop (tearly, put year(tearly)::0);
Put / "output";
Loop (tearly, put opt_y(tearly)::3);
Put / "pccon";
Loop (tearly, put opt_cpc(tearly)::3);
Put / "savrate";
Loop (tearly, put opt_s(tearly)::4);
Put / "indem";
Loop (tearly, put opt_indem(tearly)::4);
Put / "sigma";
Loop (tearly, put opt_sigma(tearly)::4);
Put / "temp";
Loop (tearly, put opt_tatm(tearly)::3);
Put / "conc";
Loop (tearly, put opt_mat(tearly)::3);
Put / "soc cost carbon";
Loop (tearly, put opt_tax(tearly)::2);
Put / "intrate";
```

```
Loop (tearly, put opt_ri(tearly)::3);
Put / "discrate";
Loop (tearly, put opt_rr(tearly)::5);
Put / "prod";
Loop (tearly, put opt_al(tearly)::5);
Put / "exogforc";
Loop (tearly, put opt_forcoth(tearly)::3);
Put / "pop";
Loop (tearly, put opt_l(tearly)::3);
Put / "carbon tax";
Loop (tearly, put opt_mcemis(tearly)::4);
Put / "margy";
Loop (tearly, put opt_yy(tearly)::3);
Put / "margc";
Loop (tearly, put opt_cc(tearly)::5);
Put / "miu";
Loop (tearly, put opt_miu(tearly)::3);
Put / "total emissions";
Loop (tearly, put opt_wem(tearly)::3);
Put / "interest rate";
Loop (tearly, put opt_ri(tearly)::4);
Put / "damages";
Loop (tearly, put opt_dam(tearly)::3);
Put / "abatement cost";
Loop (tearly, put opt_abate(tearly)::2);
Put /"objective function";
Put opt_utility::3;

*$include put_base25_early.gms

* put file for 250 year no control

Put / "Base run with no controls for 250 yrs";
Put / "year";
Loop (tearly, put year(tearly)::0);
Put / "output";
Loop (tearly, put base25_y(tearly)::3);
Put / "pccon";
Loop (tearly, put base25_cpc(tearly)::3);
Put / "savrate";
Loop (tearly, put base25_s(tearly)::4);
Put / "indem";
Loop (tearly, put base25_indem(tearly)::4);
Put / "sigma";
Loop (tearly, put base25_sigma(tearly)::4);
Put / "temp";
```

```
Loop (tearly, put base25_tatm(tearly)::3);
Put / "conc";
Loop (tearly, put base25_mat(tearly)::3);
Put / "soc cost carbon";
Loop (tearly, put base25_tax(tearly)::2);
Put / "intrate";
Loop (tearly, put base25_ri(tearly)::3);
Put / "discrate";
Loop (tearly, put base25_rr(tearly)::5);
Put / "prod";
Loop (tearly, put base25_al(tearly)::5);
Put / "exogforc";
Loop (tearly, put base25_forcoth(tearly)::3);
Put / "pop";
Loop (tearly, put base25_l(tearly)::3);
Put / "carbon tax";
Loop (tearly, put base25_mcemis(tearly)::4);
Put / "margy";
Loop (tearly, put base25_yy(tearly)::3);
Put / "margc";
Loop (tearly, put base25_cc(tearly)::3);
Put / "miu";
Loop (tearly, put base25_miu(tearly)::3);
Put / "total emissions";
Loop (tearly, put base25_wem(tearly)::3);
Put / "interest rate";
Loop (tearly, put base25_ri(tearly)::4);
Put / "damages";
Loop (tearly, put base25_dam(tearly)::2);
Put / "abatement cost";
Loop (tearly, put base25_abate(tearly)::2);
Put /"objective function";
Put base25_utility::3;

*$include put_hotel_early.gms

* put file for hotelling results

Put / "Hotelling rents run";
Put / "year";
Loop (tearly, put year(tearly)::0);
Put / "output";
Loop (tearly, put hotel_y(tearly)::3);
Put / "pccon";
Loop (tearly, put hotel_cpc(tearly)::3);
Put / "savrate";
```

```
Loop (tearly, put hotel_s(tearly)::4);
Put / "indem";
Loop (tearly, put hotel_indem(tearly)::4);
Put / "sigma";
Loop (tearly, put hotel_sigma(tearly)::4);
Put / "temp";
Loop (tearly, put hotel_tatm(tearly)::3);
Put / "conc";
Loop (tearly, put hotel_mat(tearly)::3);
Put / "soc cost carbon";
Loop (tearly, put hotel_tax(tearly)::2);
Put / "intrate";
Loop (tearly, put hotel_ri(tearly)::3);
Put / "discrate";
Loop (tearly, put hotel_rr(tearly)::5);
Put / "prod";
Loop (tearly, put hotel_al(tearly)::5);
Put / "exogforc";
Loop (tearly, put hotel_forcoth(tearly)::3);
Put / "pop";
Loop (tearly, put hotel_l(tearly)::3);
Put / "carbon tax";
Loop (tearly, put hotel_mcemis(tearly)::4);
Put / "margy";
Loop (tearly, put hotel_yy(tearly)::3);
Put / "margc";
Loop (tearly, put hotel_cc(tearly)::3);
Put / "miu";
Loop (tearly, put hotel_miu(tearly)::3);
Put / "total emissions";
Loop (tearly, put hotel_wem(tearly)::3);
Put / "interest rate";
Loop (tearly, put hotel_ri(tearly)::4);
Put / "damages";
Loop (tearly, put hotel_dam(tearly)::5);
Put / "abatement cost";
Loop (tearly, put hotel_abate(tearly)::5);
Put /"objective function";
Put hotel_utility::3;

*$include put_opt_late.gms

Put / "optimal run";
Put / "year";
Loop (tlate, put year(tlate)::0);
Put / "output";
```

```
Loop (tlate, put opt_y(tlate)::3);
Put / "pccon";
Loop (tlate, put opt_cpc(tlate)::3);
Put / "savrate";
Loop (tlate, put opt_s(tlate)::4);
Put / "indem";
Loop (tlate, put opt_indem(tlate)::4);
Put / "sigma";
Loop (tlate, put opt_sigma(tlate)::4);
Put / "temp";
Loop (tlate, put opt_tatm(tlate)::3);
Put / "conc";
Loop (tlate, put opt_mat(tlate)::3);
Put / "soc cost carbon";
Loop (tlate, put opt_tax(tlate)::2);
Put / "intrate";
Loop (tlate, put opt_ri(tlate)::3);
Put / "discrate";
Loop (tlate, put opt_rr(tlate)::5);
Put / "prod";
Loop (tlate, put opt_al(tlate)::5);
Put / "exogforc";
Loop (tlate, put opt_forcoth(tlate)::3);
Put / "pop";
Loop (tlate, put opt_l(tlate)::3);
Put / "carbon tax";
Loop (tlate, put opt_mcemis(tlate)::4);
Put / "margy";
Loop (tlate, put opt_yy(tlate)::3);
Put / "margc";
Loop (tlate, put opt_cc(tlate)::7);
Put / "miu";
Loop (tlate, put opt_miu(tlate)::3);
Put / "total emissions";
Loop (tlate, put opt_wem(tlate)::3);
Put / "interest rate";
Loop (tlate, put opt_ri(tlate)::4);
Put / "damages";
Loop (tlate, put opt_dam(tlate)::2);
Put / "abatement cost";
Loop (tlate, put opt_abate(tlate)::2);
Put /"objective function";
Put opt_utility::3;

*$include put_base25_late.gms
```

```
* put file for 250 year no control

Put / "base run with no controls for 250 yrs";
Put / "year";
Loop (tlate, put year(tlate)::0);
Put / "output";
Loop (tlate, put base25_y(tlate)::3);
Put / "pccon";
Loop (tlate, put base25_cpc(tlate)::3);
Put / "savrate";
Loop (tlate, put base25_s(tlate)::4);
Put / "indem";
Loop (tlate, put base25_indem(tlate)::4);
Put / "sigma";
Loop (tlate, put base25_sigma(tlate)::4);
Put / "temp";
Loop (tlate, put base25_tatm(tlate)::3);
Put / "conc";
Loop (tlate, put base25_mat(tlate)::3);
Put / "soc cost carbon";
Loop (tlate, put base25_tax(tlate)::2);
Put / "intrate";
Loop (tlate, put base25_ri(tlate)::3);
Put / "discrate";
Loop (tlate, put base25_rr(tlate)::5);
Put / "prod";
Loop (tlate, put base25_al(tlate)::5);
Put / "exogforc";
Loop (tlate, put base25_forcoth(tlate)::3);
Put / "pop";
Loop (tlate, put base25_l(tlate)::3);
Put / "carbon tax";
Loop (tlate, put base25_mcemis(tlate)::4);
Put / "margy";
Loop (tlate, put base25_yy(tlate)::3);
Put / "margc";
Loop (tlate, put base25_cc(tlate)::3);
Put / "miu";
Loop (tlate, put base25_miu(tlate)::3);
Put / "total emissions";
Loop (tlate, put base25_wem(tlate)::3);
Put / "interest rate";
Loop (tlate, put base25_ri(tlate)::4);
Put / "damages";
Loop (tlate, put base25_dam(tlate)::2);
Put / "abatement cost";
```

```
Loop (tlate, put base25_abate(tlate)::2);
Put /"objective function";
Put base25_utility::3;

*$include put_hotel_late.gms

* put file for hotelling results

Put / "hotelling rents run";
Put / "year";
Loop (tlate, put year(tlate)::0);
Put / "output";
Loop (tlate, put hotel_y(tlate)::3);
Put / "pccon";
Loop (tlate, put hotel_cpc(tlate)::3);
Put / "savrate";
Loop (tlate, put hotel_s(tlate)::4);
Put / "indem";
Loop (tlate, put hotel_indem(tlate)::4);
Put / "sigma";
Loop (tlate, put hotel_sigma(tlate)::4);
Put / "temp";
Loop (tlate, put hotel_tatm(tlate)::3);
Put / "conc";
Loop (tlate, put hotel_mat(tlate)::3);
Put / "soc cost carbon";
Loop (tlate, put hotel_tax(tlate)::2);
Put / "intrate";
Loop (tlate, put hotel_ri(tlate)::3);
Put / "discrate";
Loop (tlate, put hotel_rr(tlate)::5);
Put / "prod";
Loop (tlate, put hotel_al(tlate)::5);
Put / "exogforc";
Loop (tlate, put hotel_forcoth(tlate)::3);
Put / "pop";
Loop (tlate, put hotel_l(tlate)::3);
Put / "carbon tax";
Loop (tlate, put hotel_mcemis(tlate)::4);
Put / "margy";
Loop (tlate, put hotel_yy(tlate)::3);
Put / "margc";
Loop (tlate, put hotel_cc(tlate)::3);
Put / "miu";
Loop (tlate, put hotel_miu(tlate)::3);
Put / "total emissions";
```

```
Loop (tlate, put hotel_wem(tlate)::3);
Put / "interest rate";
Loop (tlate, put hotel_ri(tlate)::4);
Put / "damages";
Loop (tlate, put hotel_dam(tlate)::5);
Put / "abatement cost";
Loop (tlate, put hotel_abate(tlate)::5);
Put /"objective function";
Put hotel_utility::3;
```

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